NANOFIBER FILTER MEDIA FOR AIR FILTRATION

A Dissertation

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ABSTRACT

Nanofibers have higher capture efficiencies in comparison to microfibers in the submicron particle size range of 100-500 nm because of small fiber diameter and increased surface area of the fibers. Pressure drop across the filter increases tremendously with decrease in fiber diameter in the continuum flow regime. Nanofibers with fiber diameter less than 300 nm are in the slip flow regime as a consequence of which steep increase in pressure drop is considerably reduced due to slip effect. The outlet or inlet gases have broad range of particle size distribution varying from few micrometers to nanometers. The economic benefits include capture of a wide range of particle sizes in the gas streams using compact filters composed of nanofibers and microfibers.

Electrospinning technique was used to successfully fabricate polymeric and ceramic nanofibers. The nanofibers were long, continuous, and flexible with diameters in the range of 200 – 300 nm. Nanofibers were added to the filter medium either by mixing microfibers and nanofibers or by directly electrospinning nanofibers as thin layer on the surface of the microfiber filter medium. Experimental results showed that either by mixing Nylon 6 nanofibers with B glass fibers or by electrospinning Nylon 6 nanofibers as a thin layer on the surface of the microfiber medium in the surface area ratio of 1 which is 0.06 g of nanofibers for 2 g of microfibers performed better than microfiber
filter media in air filtration tests. This improved performance is consistent with numerical modeling. The particle loading on a microfibrous filter were studied for air filtration tests. The experimental and modeling results showed that both pressure drop and capture efficiency increased with loading time. Nanofiber filter media has potential applications in many filtration applications and one of them being hot gas filtration.

Ceramic nanofibers made of alumina and titania nanofibers can withstand in the range of 1000°C. Ceramic nanofibers filter media were fabricated by mixing alumina microfibers (SAFFIL) and alumina nanofibers. The appropriate binders were tested for ceramic filter media. The ceramic filter media were tested for aerosol filtration.
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CHAPTER I

INTRODUCTION

1.1 Background and overview of work

Atmospheric air contains $140 \times 10^6$ particles/m$^3$ and 80% of these particles are in the range of 2 µm [1]. There is a tremendous interest in filtration of tiny particles and particle’s emission in air because of the detrimental effect of the aerosol particles on human health and environment. In 2002, U.S government announced two air quality proposals to address the control of emissions of Sulfur dioxide (SO$_2$), Nitric oxide (NOX) and mercury (Hg) [2]. Both NO$_x$ and SO$_2$ gases contribute to particulate matter of particles size of 2.5 micron or less (PM2.5). The emission caps would be imposed in two phases: 2010 and 2018 [2]. Because of stringent regulations, there is an increasing demand for highly efficient filters to capture particles less than 2 microns.

Experimental measurements and theoretical calculations showed nanofiber filter media to be extremely efficient at trapping airborne contaminants [3]. The high filtration efficiency is a direct result of the submicron fiber size. Thus, nanofiber filter media can be solution for above challenges.

Different methods can be used to produce nanofibers such as drawing [4], template synthesis [5-6], phase separation [7], self assembly [8-9] and electrospinning [10-11]. Among the different methods to produce nanofibers, electrospinning is most
popular method because of its low cost, simplicity, formation of continuous nanofibers, and it does not require additional expensive purification during the fabrication process. Ceramic nanofibers have also been fabricated using the electrospinning method.

Ceramic filter media have potential applications for hot gas filtration in the temperature range of 1000°C. In today’s process and power industries, temperatures of dust laden hot gases are well above 1000°C. Economically, it would be convenient to use the high energy potential of hot waste gases in recovery boilers for producing electricity[12]. However, dust contained in hot gases results in a rapid failure of any heat recuperators. In practice, two types of equipment are used to clean waste gases from the dust are bag filters and electric filters. The gases need to be cooled in the range of 250-350°C before they are transferred to this equipment, since they cannot operate at such high temperatures. The cooled cleaned gases have lower enthalpy and use of any recuperators for recovering heat from these gases becomes economically ineffective.

In order to take advantage of high temperature of hot waste gases for producing electricity, submicron particles less than 1 micron need to be filtered out from hot gases to protect turbine and recuperators from dust induced damage. This requirement to capture particle size less than 1 micron from hot gases exceeds the current requirements for environmental protection but may have economic incentive. Thus, ceramic nanofibers can be added to microfiber filter media, which can withstand high temperature as well as capture sub micron particles of hot gases.
In this present work, our main focus is to understand the performance of nanofiber filter media for air filtration applications by comparing with microfiber filter media and fabricate ceramic nanofiber filter media for hot gas filtration. Nanofibers are fabricated using the electrospinning method. Various amounts of electropsun nanofibers are augmented with microfiber filter media using two different approaches to form composite filter media. In the first method, composite filter media are formed by directly electrospinning nanofibers as thin layer on the surface of microfiber filter media. In the second method, electrospun nanofibers are mixed with microfibers to form mixed composite media. The performances of composite filter media and microfiber filter media are compared for aerosol testing. Mathematical models are developed to compare the experimental results and modeling results for composite filter media.

The loading tests of solid particles are carried out using an automated filter tester (TSI 8130) for microfibrous filter media. Mathematical models are developed to compare the modeling and experimental results for particle loading. Ceramic nanofibers are fabricated using the electrospinning technique. The ceramic composite filter media comprising of ceramic nanofibers, ceramic microfibers, and binders, are successfully developed to withstand high temperatures. Due to the non-availability of a hot gas filtration set up, the filter media are tested for aerosol testing at room temperature. Mathematical modelings are developed to predict the performance of composite filter medium at high temperatures.
1.2 Problem statement

The overall capture efficiency has a minimum defining the Most Penetrating Particle Size range (MPPS) of 100 – 500 nm for a microfibrous filter medium for a fiber diameter of 10 micron with a porosity of 90% as shown in Figure 1.1[13-14]. Because of the new EPA regulations, it is of interest to capture submicron particles. Nanofiber filter media can have a huge impact on the performance of the filter efficiencies compared to other micron sized filter media because of higher capture efficiencies of submicron particles.

Figure 1.1 Overall capture efficiency of a microfibrous filter medium [14].

One of potential applications of ceramic filter medium is hot gas filtration. Currently, hot waste gases in the range of 1000°C are cooled to 250°C due to non-availability of filter medium to withstand high temperatures. Thus, the fabrication of ceramic nanofiber filter media to withstand high temperature in the range of 1000°C will
improve the efficiency of energy consumption because high thermal energy of hot waste
gases can be used for producing electricity.

1.3 Objectives

The main objectives of this work are

1) Fabricate nanofibers using electrospinning technique
   a) Polymeric nanofibers.
   b) Ceramic nanofibers to withstand high temperature in the range of 1000°C.

2) Find a suitable binder
   a) Binder to bind polymeric nanofibers and glass microfibers to form composite filter media.
   b) Binder which can withstand high temperature in the range of 1000°C for ceramic composite filter medium by providing the structural support to the filter medium

3) Fabricate composite filter media.
   a) Fabricate composite filter media by augmenting nanofibers to the microfiber filter medium.
   b) Nanofibers can be augmented to microfiber filter medium in two different methods. In the first approach, nanofibers can be added as a thin layer on the surface of the microfiber filter medium. In the second approach, nanofibers can be mixed with microfibers to form mixed composite medium.
   c) Vary the amount of nanofibers added to the microfiber filter media.
4) Develop a model for composite filter media
   a) To develop a mathematic model based on single fiber theory to predict
      filter performance trend for varying amount of nanofibers added to the
      microfiber filter medium.
   b) A mathematical model to be developed to predict the filter
      performance of composite filter media at high temperatures.

5) Develop a model for particle loading on microfibrous filter medium
   a) To predict filter performance trend such as pressure drop and capture
      efficiency when loaded with solid particles. Model should consider the
      effect of accumulated particles on the fibrous medium.

6) Develop a model to compare the filter performance of fibrous, granular and
    monolith filter
   a) A mathematical model to be developed to compare the filter
      performance of three different filter structures such as fibrous, granular
      and monolith to determine the most efficient filter structure at high
      temperatures

7) Aerosol testing of filter medium
   a) Composite filter media for varying amount of nanofibers will be tested
      using automated filter tester (TSI 8130) and will be compared with
      modeling results
   b) Particle loading on microfibrous filter media will be done using TSI
      8130 and will be compared with modeling results
1.4 Hypothesis

1. It is hypothesized that by adding nanofibers to the microfiber filter medium, capture efficiency of the filter medium will be improved.

2. It is hypothesized that filter performance will be enhanced by adding the optimum amount of nanofibers to the microfiber filter medium.

3. It is hypothesized that the ceramic nanofiber filter medium comprising of microfibers and nanofibers will withstand high temperatures and have higher capture efficiency.

1.5 Dissertation outline

This dissertation is divided into nine chapters. Chapter II contains literature review about the aerosol particles, fabrication of nanofibers using electrospinning, and nanofiber filter media for air filtration applications. Chapter III is about developing the model for composite filter medium for room temperature and high temperature gas filtration. Chapter IV is about developing the model for particle loading on a fibrous filter medium. Chapter V has the modeling comparison of fibrous, granular and monolith filter structure at high temperature. Chapter VI describes the synthesis techniques used for the development of polymer and ceramic nanofibers. Chapter VII has the information about the development of nanofiber enhanced filter media for air filtration and hot gas filtration applications. Chapter VIII is the comparison of modeling and experimental results for nanofiber filter media for air filtration as well as modeling and experimental comparison for particle loading on a fibrous filter media. The last chapter contains the conclusions drawn from this research and gives the recommendations for the work.
CHAPTER II

LITERATURE REVIEW

2.1 Aerosol particles

The term ‘aerosol’ refers to a disperse system with a gas phase medium and a solid or liquid disperse phase that contains particles varying from 0.001 µm to more than 100 µm [15]. The sources of atmospheric aerosols may be natural or anthropogenic (related to human activities). The natural sources are soil and rock debris, sea salt, volcanic dust, pollen, viruses, and bacteria. Particles from transportation, electric power generation, and industrial process are related to human activities and they constitute less than 10 – 50% of the global particulate emissions [16].

Aerosols are classified based on the physical form of the particles as bioaerosol, cloud, dust, fume, haze, mist, fog, smog, smoke and spray [17]. Particle size, which is usually the particle diameter, is the fundamental parameter for characterizing the aerosol behavior [17]. Particle size are classified as

Nanoparticles - particles having particle diameter less than 50 nm.
Ultrafine particles – particles with diameter about 100 nm.
Submicrometer particles – particles having the diameter smaller than 1 µm.
Micrometer particles – particles with diameter between 1 and 10 µm.
Electric utility generating facilities are one of the major sources of air pollution [2]. The combustion of fossil fuels such as petroleum, natural gas and coal, which accounts for about two-thirds of U.S electricity generation, results in the emission of gases. These gases pose risks to human health and welfare includes several pollutants such as particulate matter (PM), sulfur dioxide (SO₂), nitrogen oxides (NOₓ) and mercury (Hg). Particulate matter, SO₂, and NOₓ are regulated under the Clean Air Act (CAA), and the Environmental Protection Agency (EPA). Table 2.1 shows the annual cap on various emissions based on Clear skies Initiative [2].

Table 2.1 Annual cap on various emissions based on the Clear Skies legislation bill [2]

<table>
<thead>
<tr>
<th>Type of emission</th>
<th>Emission in 2000 (tons)</th>
<th>Clear Skies Initiative Emissions Cap</th>
<th>Reduction at full implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First Phase reduction</td>
<td>Second Phase reduction</td>
</tr>
<tr>
<td>Hg</td>
<td>48</td>
<td>26 tons in 2010</td>
<td>15 tons in 2018</td>
</tr>
<tr>
<td>SO₂</td>
<td>11.2 million</td>
<td>4.5 million tons in 2010</td>
<td>3 million tons in 2018</td>
</tr>
<tr>
<td>NOₓ</td>
<td>5.1 million</td>
<td>2.1 million tons in 2008</td>
<td>1.7 million tons in 2018</td>
</tr>
</tbody>
</table>

Table 2.2 provides the estimates of SO₂, NOₓ, and CO₂ emissions from electric generating facilities [18]. The decrease in trend of SO₂, NOₓ emissions are due to evolution of air pollution controls over time. Additional measures are in the development, particularly with respect to NOₓ and SO₂ because both gases contribute to PM₂.₅. CO₂ gases may pose indirect risks, which may contribute to global warming.
Table 2.2 Emissions from U.S. Fossil-Fuel Electric Generating Plants (thousands of metric tons) [18].

<table>
<thead>
<tr>
<th>Emissions</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO$_2$</td>
<td>12,445</td>
<td>11,297</td>
<td>10,966</td>
<td>10,515</td>
<td>10.643</td>
<td>10,307</td>
</tr>
<tr>
<td>NO$_X$</td>
<td>5,732</td>
<td>5,380</td>
<td>5,045</td>
<td>4,802</td>
<td>4,326</td>
<td>3,951</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>2,326,558</td>
<td>2,429,394</td>
<td>2,379,603</td>
<td>2,395,232</td>
<td>2,415,804</td>
<td>2,444,443</td>
</tr>
</tbody>
</table>

The EPA projects that, by 2020, the significant benefits to public health from Clear Skies would include more than 14,000 avoided premature deaths and total $110 billion per year for an annual cost of $6.3 billion. Clear Skies would also help State and local governments attain the National Ambient Air Quality Standards (NAAQS) for fine particles (PM 2.5) and ozone.

EPA’s Heavy-Duty Highway Diesel rule (the “2007 Highway Rule”) mandates a 97 percent reduction in the sulfur content of highway diesel fuel from its current level of 500 parts per million (ppm) to 15 ppm. Thus, by addressing diesel fuel and engines, the environmental benefits are 2.6 million tons of NO$_X$ emissions will be reduced each year, PM will be reduced by 110,000 tons per year [19]. The health benefits from this program are prevention of 8,300 premature deaths and once this program is fully implemented, it will result in more than $70 billion annually in environmental and public health benefits.

Nitrogen oxides from diesel engines, automotives and power plants are the major source of contaminants of particulate matter and ground level ozone. Table 2.3 list the amount of contaminants generated from the various industrial process [12, 20]. Table 2.4
lists the particle size distribution of dusts from various sources [1]. There is a necessity for advanced filters to meet the new demands of protecting human health and the environment.

Table 2.3 Amounts of contaminants carried by various exit gases [20]

<table>
<thead>
<tr>
<th>Source</th>
<th>Contaminant amounts generated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steelmaking furnace</td>
<td>0.02 kg/m³</td>
</tr>
<tr>
<td>Non-ferrous metallurgy</td>
<td>0.0015-0.2 kg/m³</td>
</tr>
<tr>
<td>Alumina Calcination kilns</td>
<td>1.5 kg/m³</td>
</tr>
<tr>
<td>Rotary kiln of diameter, 4.5m and length, 170m</td>
<td>18000-20000 kg/hour</td>
</tr>
<tr>
<td>Dolomite calcination kiln of diameter, 3.6m and length, 90m</td>
<td>7000-8000 kg/hour</td>
</tr>
</tbody>
</table>

Table 2.4 Particle size distribution of contaminants from various sources [1]

<table>
<thead>
<tr>
<th>Type of contaminant</th>
<th>Particle size distribution(µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuously suspended dust</td>
<td>0.0001 - 1.0</td>
</tr>
<tr>
<td>Viruses</td>
<td>0.0001 - 0.01</td>
</tr>
<tr>
<td>Inside dust</td>
<td>0.0001 – 100</td>
</tr>
<tr>
<td>Fumes</td>
<td>0.001-0.1</td>
</tr>
<tr>
<td>Metallurgical fumes and dust</td>
<td>0.001-100</td>
</tr>
<tr>
<td>Cupola dust</td>
<td>0.003-100</td>
</tr>
<tr>
<td>Welding fumes</td>
<td>0.01-1</td>
</tr>
<tr>
<td>Carbon black</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Tobacco smoke</td>
<td>0.01-10</td>
</tr>
<tr>
<td>Oil mist</td>
<td>0.01-10</td>
</tr>
<tr>
<td>Dry ash</td>
<td>0.1-100</td>
</tr>
<tr>
<td>Industrial dusts</td>
<td>1-1000</td>
</tr>
</tbody>
</table>
2.2 Currently available air filters

Table 2.5 list the type of filters and their efficiency in the particle size range.

Microfibers are efficient in capturing particles 1 micron and above. Nanofiber filter media are required to capture submicron particles less than 1 micron.

Table 2.5 Type of filters and range of particle size removal [1]

<table>
<thead>
<tr>
<th>Type of filters</th>
<th>Range of particle size, µm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microfibers</td>
<td>0.01 - 10</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>0.001-10</td>
</tr>
<tr>
<td>Membrane</td>
<td>0.005-12</td>
</tr>
<tr>
<td>Paper</td>
<td>1-100</td>
</tr>
<tr>
<td>Sintered metals</td>
<td>1-100</td>
</tr>
<tr>
<td>Fabric dust collectors</td>
<td>0.01-100</td>
</tr>
</tbody>
</table>

2.3 Nanofiber filter media for air filtration applications

Previous work shows that capture efficiency is inversely proportional to the fiber diameter for fibrous filter media [21]. Nanofibers are in slip flow regime because nanofibers diameters are comparable to mean free path of air molecules. As a consequence of which, steep increase in pressure drop with decreasing fiber diameter is considerably reduced due to slip effect. Nanofibers have a distinct advantage of high surface area per unit volume because of small fiber diameter and can capture sub micron particles efficiently [22]. It has been shown that nanofibers have potential application in filtration [23].

12
2.4 Nanofibers

According to fiber science related literature, fibers with diameters below 100 nm are generally classified as nanofibers [24-25]. Nanofibers are solid state linear nanomaterials which are flexible and have an aspect ratio greater than 1000:1 [22].

2.5 Nanofibers applications

Nanofibers offer a broad range of applications in areas such as photonics, sensors, catalysis, medicine, and filtration as shown in Figure 2.1

Figure 2.1 Nanofibers applications
2.6 Characterization of nanofibers

Nanofibers can be characterized by four different ways as given below:

- Geometrical characterization
- Chemical characterization
- Transport characterization
- Mechanical characterization

Each of these categories will be explained in the following.

2.6.1 Geometrical characterization:

Geometric properties of nanofibers and fibrous mats of nanofibers are important. Properties including fiber diameter, cross-section shape, and surface roughness are important. Mat properties such as fiber distribution, fiber orientation, porosity, and web integrity are characterized using Scanning Electron Microscope (SEM), Field Emission Scanning Electron Microscopy (FESEM), Transmission Electron Microscopy (TEM) and Atomic Force Microscopy (AFM) [26-29]. AFM can also be used to characterize the roughness of the fibers.

2.6.2 Chemical characterization:

Molecular structure of nanofibers can be characterized using Fourier transform infrared (FTIR) and nuclear magnetic resonance (NMR) techniques [30]. The macromolecules configuration in nanofibers can be characterized using optical birefringence [31-33], wide-angle X-ray diffraction (WAXD), small angle X-ray scattering (SAXC) and differential scanning calorimeter (DSC) [31, 34]. Surface chemical properties can be determined using X-ray Photoelectron Spectroscopy XPS, water contact angle measurement, and Fourier Transform Infrared - Attenuated Total
Reflectance (FTIR-ATR) analyses [35]. Both structure and intermolecular interactions can be determined for nanofibers made from polymer blends using XPS and FTIR-ATR [35].

2.6.3 Transport Characterization:

A dynamic moisture vapor permeation cell was used for the measurement of air and vapor transport properties of electrospun nanofibrous mats [36]. The apparatus measured both the water vapor diffusion and gas convection properties of electrospun fiber mats [56]. Electrical transport properties of nanofibrous mats have been studied [37].

2.6.4 Mechanical characterization:

Although the literature for mechanical properties of single nanofibers is sparse, there have been some reported findings on the mechanical properties of mat of nanofibers [38-39]. The tensile strength of a nanofibrous mat was found to be similar to that of a natural skin [35]. Electrospun nonwoven mats were found to have different properties in different directions, anisotropy, when the membranes were produced on a rotating drum [38-39].

2.7 General Properties of nanofibers and resulting mats:

If one were to generalize the properties of nanofibers and mats produced from nanofibers they would be as listed below.

- Large surface area to volume ratio (this ratio for nanofibers can be as high as 1000 times compared to that of a microfibers) [35]
- Flexibility in surface functionalities [35]
- Superior directional strength
- Small diameter
- Highly oriented crystalline structures (much superior mechanical stiffness and tensile strength along the fibers) [35]
- Thermal and chemical stability
- Low ohmic resistance
- Surface properties
- High aspect ratio (length to diameter ratio)
- Increased control of pore size in mats

The combination of all the above properties makes nanofibers a preferred material for many applications ranging from clothing to reinforcement structures. Small fiber diameters are considered to be the main reason for the increase in the surface area, bio-reactivity, electronic properties and mechanical properties of the nanofibers. One of the most significant characteristics of nanofibers is the availability of surface area per unit mass. In nanofibers that are 3 nm in diameter and contain about 40 molecules about half of those molecules were found to be on the surface [22]. High surface area of nanofibers provides a remarkable capacity for the attachment or release of functional groups, absorbed molecules, and ions.

2.8 Methods to produce nanofibers:

They are many different methods that have been used to produce nanofibers. A few of them are listed below

- Drawing [4]
- Template synthesis [5-6]
- Phase separation [7]
- Self-assembly [8-9]
- Electrospinning [10-11]

Many of these methods have advantages for specific fiber formations, but they do have some disadvantages from processing standpoint. Viscoelastic materials can forgo large deformation and are capable of being pulled into nanofibers through a drawing process [4]. The drawing process is one where the material is mechanically stretched into the desired shape. The disadvantage of the drawing process is that the material must possess enough ductility to undergo large deformations without failure [35]. In template synthesis, nanoporous membranes have been used as a template to produce nanofibers of solid (fibril) or hollow (tubule) shape in the template synthesis process [5-6]. A disadvantage of this method is that it cannot make continuous nanofibers.

The phase separation process requires long time frames to transfer the solid polymer into the nano-porous foam [35]. Self-assembly is a process in which components organize themselves into some preferential patterns, which may have useful nanoscale structures. The self-assembly process also takes long periods of time as does the phase separation process to produce continuous polymer nanofibers [35].

Electrospinning is similar to drawing, but uses an electric field to pull the polymer instead of a mechanical force. The electric field causes a droplet of a polymer (usually in the form of a solution) to form a cone shape. At the apex of the cone, the flow field is unstable and the material launches a jet. As the jet moves away from the drop, charge imbalances cause the jet to bend and stretch. The stretching causes the jet diameter to decrease, and the solvent in the polymer jet solution evaporates, causing the jet to stiffen into the form of a fiber so that the diameter is in the nanometer scale range. The
formation process is relatively fast and continuous fibers are produced. Scale-up also appears to be possible. The electrospinning technique appears to be a reasonable approach to produce continuous nanofibers [35].

2.9 Electrospinning

Electrospinning is a process by which a polymer solution can be spun into smaller diameter fibers using a high potential electric field [40]. The apparatus used for electrospinning is simple in construction. It consists of a high voltage source, a syringe, a pump to carry the solution to the syringe and a conducting collector. The conducting collector could be of any shape such as flat plate or rotating drum. A schematic of the electrospinning process is shown in Figure 2.2.

Figure 2.2 Conventional Electrospinning set up.
Many researchers have used an apparatus similar to the one shown in Figure 2.2 with slight modifications depending on their area of interest. The polymer solution that is to be spun is forced through a needle by a syringe pump or flows from a capillary tube or pipette by gravity to form a pendant drop of the polymer at the tip of the capillary.

A high voltage potential is applied to the polymer solution through an immersed electrode, thereby inducing free charges into the polymer solution. These charged ions move in response to the applied electric field towards the electrode of opposite polarity. At the tip of the capillary, the pendant hemispherical polymer drop takes a cone like projection in the presence of the electric field. When the applied potential reaches a critical value required to overcome the surface tension of the liquid, a jet of liquid is ejected from the cone tip.

After the initiation from the cone, the jet undergoes a chaotic motion or bending instability and it is directed towards the oppositely charged collector, which collects the charged fibers. As the jet travels through the atmosphere, the solvent evaporates, leaving behind a dry fiber on the collecting device. For low viscosity solutions, the jet breaks up into droplets, while for high viscosity solutions it travels to the collector as fiber jets.

2.10 History of Electrospinning

The term “Electrospinning” was derived from “electrostatic spinning” and usage of this term increased since 1994 [35]. The idea of electrospinning dates back more than 100 years earlier. The electrospinning process was first patented by J.F. Cooley in February 1902 and by W.J. Morton in July 1902 [41-42]. In 1934, Formhals patented his
first invention for producing polymer filaments using electric charges [43]. Though the method of producing polymer filament using an electric field had been investigated long time before, it wasn’t popular due to technical difficulties in spinning methods, such as fiber drying and collection. It has gained popularity with the recent push in nanotechnology. Formhals’s spinning process had a movable thread collecting device to collect the threads in a stretched condition, like that of a spinning drum in the conventional spinning. Formhals’s process was successful in collecting the threads aligned parallel on to the receiving device in such a way that it can be unwound continuously. In his first patent, Formhals reported the spinning of polymer solution using cellulose acetate as the polymer and acetone as the solvent for the production of fibers [43].

Formhals first spinning method has some technical disadvantages due to the short distance between the nozzle and collection zones. It was too difficult to completely dry fibers due to short distances. In his subsequent patent, Formhals overcame the above mentioned drawbacks by changing the distance between the nozzle and collection zones in order to increase the drying time and ended up in forming electrospun fibers [44].

Subsequently in 1940, Formhals patented another method for producing composite fiber webs from multiple polymers by electrostatically spinning polymer fibers on a moving base substrate [45]. In 1966, Simons patented an apparatus for the production of non-woven fabrics of ultra thin and very light in weight using the electrospinning technique. He found out that low viscous solutions produce shorter and finer fibers whereas more viscous solutions produce continuous fibers [46]. In the 1960’s,
much research on jet forming process were done. In 1969, Taylor studied the shape of the polymer droplet produced at the tip of the needle when an electric field is applied [47]. He showed that the polymer droplet was in the shape of the cone and the jets were ejected from the vertices of the cone [47]. Taylor examined with different viscous fluids and determined that an angle of 49.3 degrees was required to balance the surface tension of the polymer with the electrostatic forces. The conical shape of the jet is very important because it defines the beginning of the extensional velocity gradients in the fiber forming process. This conical shape of the jet was later referred as the “Taylor cone” by other researchers in their literatures [40].

In subsequent years, researchers started to focus on studying the structural morphology of nanofibers. Researchers started to analyze the relationship between the structural characterization of fibers and process parameters. The structural characterization of nanofibers were done using wide-angle X-ray diffraction (WAXD), scanning electron microscope (SEM), transmission electron microscope (TEM), differential scanning calorimetry (DSC) and atomic force microscopy (AFM).

In 1971, Baumgarten was successful in generating electrospun microfibers using the polyacrylnitrile/dimethylformamide (PAN/DMF) solution and observed dependence of fiber diameters on the viscosity of the solution [48]. He also showed that diameter of the jet reaches a minimum value with an initial increase in the applied field and then increases with increasing electric fields [48]. Larrondo and Mandley were successful in producing polyethylene and polypropylene fibers from the melt with relatively larger
diameters than solvent spun fibers [49-50]. In 1987, Hayati and co-workers studied effects of electric field and observed that highly conducting fluids with increasing applied voltage produced highly unstable streams that whipped around in different directions whereas the semiconducting and insulating polymer solution produced relatively stable jets [51].

After a gap of decade or so, a sudden rise in research on electrospinning took place due to the increased knowledge on the application of nanofibers in different areas such as high efficiency filter media, protective clothing, catalyst substrates, and adsorbent materials. Nanofiber research with electrospinning gained momentum due to the work of Doshi and Reneker [52]. Figure 2.3 shows the survey of open publications related with electrospinning in the past ten years. These data were obtained based on a Sci-Finder Scholar search system with the term “Electrospinning”, as on May 26, 2010.

![Figure 2.3 Number of publications on Electrospinning versus year of publication.](image-url)
The data clearly show that electrospinning has attracted increasing attention. The electrospinning of nanofibers showed increasing potentials for applications in different engineering areas.

2.1.1 Process parameters and fiber morphology

Many parameters influence the nanofibers formation during the electrospinning process and are listed below:

1. Applied voltage
2. Concentration of polymer solution
3. Distance between syringe tip and collector
4. Molecular weight of polymer solution
5. Syringe gauge size
6. Flow rate
7. Ionic addition
8. Solvent composition
9. Temperature
10. Humidity
11. Thermal degradation
2.12 Mass production of nanofibers

In this section, we discuss about significance for mass production of nanofibers and literature review on mass production of nanofibers.

2.12.1 Significance

Most of the published works in electrospinning are based on the formation of nanofibers using one syringe needle. A lot of work has been done in the area of spinning different polymer solutions, controlling process parameters using single needles to produce nanofibers in the desirable fiber diameter range. In most published works, mass of nanofibers produced using single needle is typically 0.1 – 1.0 g/hour [53] compared to millions of tons of conventional fibers produced per annum using conventional fiber spinning methods. As a result, nanofibers are obtained in low yields, which have limited the industrial applications of electrospinning in various fields such as filtration, biomedical, catalysis, etc. Recently, more focus is on the production of nanofibers using multiple needles or other viable methods to get more yields of nanofibers. Mass production of nanofibers is of great importance to meet the current demands in the market. The nanofibers market increased from $43.2 million in 2006 to $50.3 million by the end of 2007. Global market for nanofibers products was $80.7 million for 2009 and it is estimated to be $102 million by the end of 2010 and it is expected to increase to $442.7 million in 2015 [54]. Process control and design is one of the key factors for mass production of nanofibers with desirable properties such as small fiber diameter, small fiber size distribution and more yield per hour.

2.12.2 Single needle electrospinning set up for mass production of nanofibers
The injection of compressed air has been widely used technique to achieve higher production rate than a conventional single nozzle electrospinning set up [55]. Kim et. al was successful in increasing the production rate of nanofibers by injecting the compressed air to the conventional electrospinning set up for spinning thermoplastic or thermosetting polymers [56]. However, several disadvantages have been found such as higher voltage supply, discontinuous polymer solution supply. Yoshihiro et. al carried out electrospinning using a needle with a grooved tip, from which the branches of multi-jets were formed for improving the productivity of the single needle electrospinning process [57].

2.12.3 Multi-jets from multi-needle electrospinning

The combination of a number of individual needles as the spinneret is one of the most common methods to increase nanofibers production. Needle spacing, number of needles and needle arrangements are three key parameters for multi-needle electrospinning set up. The configuration of multiple needles can be linear arrays [58-61] or two dimensional arrays such as square [60], circular and elliptic [61], hexagonal [62], etc. Only few works have been done on the study of needle configuration in the multi-needle set up. Theron et. al studied with equidistantly arranged seven or nine needles for the possibility of scale up and figured out that behavior of border jets along the linear array were different from that of central jets with respect to envelope cone and bending direction [63]. In the study of 26 needles arranged in a linear manner, jets were generated from the border needles on either side and needles closer to the center were quite inactive [61]. This phenomenon can be caused due to electric field shielding near the center
needles. The needles are spaced in such a way, that droplets suspended from the neighboring tips do not bond together during the initial stage of multi-needle electrospinning setups. Needle spacing is depended on nozzle gauge as well as on the properties of the polymer solution to be electrospun. Theron et. al designed a 3x3 matrix needle arrangement and achieved a production rate of 22.5 mL cm\(^{-2}\) min\(^{-1}\) to 22.5 L cm\(^{-2}\) min\(^{-1}\) with nine needles [63]. Kim patented a bottom up multi-needle electrospinning setup to enhance the productivity as well as to avoid polymer droplets formations on the nanofibers web [64]. The setup has a productivity of 1.0 – 1.6 mg/min per nozzle and has a capacity for 3000 – 6000 nozzles. Clogging of nozzles and solvent recycling are considered to the main disadvantages.

2.12.4 Multi-jets from needless electrospinning

Multi jet electrospinning and multi-needle electrospinning are different, where multi jets are produced using needless electrospinning set up. Yarin et. al developed a set up using the combined effect of magnetic and electric fields acting on magnetic fluid and polymer solution layers for the mass production of nanofibers using needless approach [65]. The set up consisted of lower layer of magnetic fluid followed by an upper layer of polymer solution. Under the influence of magnetic field, vertical spikes generated from the lower magnetic fluid disturbs the interface of two layer solutions as well as the free surface of the upper polymer solution. When the electric field is applied, perturbances of polymer solution become the sites for multiple jets launched towards the collector. Jirsak et. al designed a Nanospider machine which uses a semi-submerged smooth rotating cylinder as the electrode to pick up drops of solution from polymer bath and nanofibers
are spun towards the collector [66]. The production rate of Nanospider machine was 1.5 g min\(^{-1}\) m\(^{-1}\).

Dosunmu et. al used a cylindrical porous tube to form multiple jets on the surface through the inherent pores of the porous tube from the air pressurized polymer solution inside the tube and production rate was 4.2 g min\(^{-1}\) per meter tube length (Fig.2.4 (a)) [53]. Varabhas et. al used linear array of holes to form nanofibers and production rate was 0.3 – 0.5 g h\(^{-1}\) for a 13 cm long tube with 20 holes on the bottom surface of the tube (Fig. 2.4 (b) [67]. Liu et. al used compressed air or nitrogen through a nozzle at the bottom of the polymer solution to produce bubbles on the free surface of the polymer solution [68]. The electrostatic field was formed between a metal needle inside the nozzle and the grounded collector. During the electrospinning process, multiple jets are produced from many bubbles on the polymer solution. This setup was used for mass production of nanofibers. The main advantages of multi-jets from needless electrospining compared with multi-needle electrospinning are that former is free from clogging of needles.

![Figure 2.4 (a) Porous cylindrical tube [53] (b) Porous electrospinning with linear hole array [67].](image)
2.13 Introduction to air filtration

The capture efficiency and pressure drop are the parameters for filter performance. This section describes how the capture efficiency and pressure drop varies for nanofibers and microfibers.

2.13.1 Flow pattern

Gaseous flow through a filter depends on both the structure of the filter and the nature of the flow. The basic understanding of the flow field through a filter helps us in calculating the pressure drop across the filter and better understanding of the particle capture mechanism and enabling us to calculate the fiber efficiency. The first step is to calculate the flow field within a filter. Solution of flow field in the entire filter is complicated and therefore it is necessary to consider a simplified model. An isolated fiber model and single fiber theory considers the gas flow around a single fiber. In the isolated fiber model, gas flow around a fiber in a fibrous filter is estimated by considering a single cylindrical fiber in an infinite space with their axis perpendicular to air flow. Potential flow, Stokes flow and Oseen flow assumptions have been used to model the flow field around a fiber [69]. The major drawback of isolated fiber model is that it does not consider the effect of nearby fiber in the model and therefore, it is not a valid approximation to calculate pressure drop and capture efficiency of the fibers in the filter. Single fiber theory considers the effect of neighboring fibers and two common models such as Happel and Kuwabara are used to describe the flow field. Happel and Kuwabara model are almost similar except that Happel considers tangential stress to be zero and Kuwabara considers the vorticity to be zero [70-71]. These models are called cell models because flow equation is solved in a limited region and assumed to be typical of the filter.
as a whole. The greatest advantage of single fiber theory is its simplicity and it is widely
used theory for calculation of filter performance. Among the cell models, Kuwabara is
preferred because of its good description of flow velocity and it is used to analyze the
fundamental phenomena related to the pressure drop and particle capture on a fiber [72].

2.13.2 Pressure drop

Fiber diameter is an important variable for filter efficiency and pressure drop.
Flow regime around the fiber is classified based on the fiber diameter, which is given by
Knudsen number (Kn). Table 2.6 lists the flow regimes based on the Kn values.

\[
Kn = \frac{2\lambda}{d_f}
\]

where \(d_f\) = fiber diameter, \(\lambda\) = mean free path of air molecules.

<table>
<thead>
<tr>
<th>Kn value</th>
<th>Continuum</th>
<th>Slip</th>
<th>Transition</th>
<th>Molecular</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Kn &lt; 0.01)</td>
<td>(Kn &lt; 0.25)</td>
<td>(0.25 &lt; Kn &lt; 10)</td>
<td>(Kn &gt; 10)</td>
<td></td>
</tr>
</tbody>
</table>

The pressure drop across the filter using the Kuwabara model in the continuum regime is
given by [73]

\[
\Delta P = \frac{4cL \eta U}{R^2 Ku}
\]

where: Ku = Kuwabara constant, R = radius of fiber, c = packing fraction, L = filter
thickness, \(\eta\) = coefficient of viscosity, and \(U\) = air velocity
The validity of the above expression holds well, provided that the stack of fiber layers are separated by a distance at least equal to the interfiber spacing between the fibers for a clean filter [74].

For a micron size fiber in the range of 20 µm, the flow regime is in continuum flow and follows Navier-Stokes equations. Continuum flow considers “no-slip” boundary conditions because distance between air molecules (0.065 µm) is small compared to fiber diameter and hence, most of the air molecules near fiber surface collide and exchange momentum with the fiber. Thus, the velocity is zero at the fiber surface in the continuum flow and velocity gradient (dvZ/dr) is greater and therefore, drag force per unit length of fiber is larger (Fd) as compared to ultrafine fibers in the slip flow regime. This is depicted in Figure 2.5.

In the case of ultrafine fibers having diameters less than about 13 µm, the Kn > 0.01 and slip flow must be considered. The continuum flow model is modified to account for rarefaction effects due to the decrease in fiber diameter. Gas molecules near the fiber may slip past and not collide to exchange momentum with the fiber. Thus, the baricentric velocity of the gas at the fiber surface is non zero because some of the air molecules that do not collide with the fiber do not decrease their velocity. Therefore, the velocity gradient (dvZ/dr) in slip flow is lesser than in continuum flow and hence the drag force per unit length of fiber, which is proportional to the fiber diameter, is lesser as compared to a larger microfiber in continuum flow.
The pressure drop across a fiber is invariably less because of the slipping effect of air molecules when nanofibers are used compared to micron size fibers. When we consider the fiber diameter in the scale of nanofibers, aerodynamic slip effect is taken into consideration and pressure drop calculated using Kuwabara model is given by [75]

\[
\Delta P = \frac{4\eta cLU(1 + 1.996Kn)}{R^2 \left[ -\frac{1}{2} \ln(c) - 0.75 + c - \frac{c^2}{4} + 1.996Kn(-\frac{1}{2} \ln(c) - 0.25 + \frac{c^2}{4}) \right]}
\]
The above expression is valid, provided that the experiments are carried out at reduced pressure and the stack of fiber layers are separated a distance at least equal to the interfiber spacing between fibers for a clean filter [76].

The pressure drop in the free molecular flow is given by [75]

\[ \Delta P = \frac{2.29 \eta c L U}{R \lambda} \]

Molecular flow is considered only when the fiber diameter is such that \( \text{Kn} > 10 \) [75]. There is no analytical approximation for a transition flow which is in between molecular flow and slip flow.

2.13.3 Overall Filter Efficiency

Once the flow patterns based on Kuwabara cell model are known, overall filter efficiency can be calculated using single fiber efficiency. The overall filter efficiency is related to single fiber efficiency as [73]

\[ \eta_o = 1 - e^{-\alpha L} \]

where: \( \eta_o = \) Overall filter efficiency, \( \alpha = \) layer efficiency = \( \frac{4c E_s}{\pi d_f} \), \( E_s = \) Total single fiber efficiency

Total Single fiber efficiency is obtained as a combination of Single fiber efficiency due to Interception, impaction, diffusion, gravity and electrostatic charge on fiber [75].

\[ 1 - E_s = (1 - E_R)(1 - E_I)(1 - E_D)(1 - E_E)(1 - E_G) \]

Where: \( E_R = \) Single fiber efficiency due to direct interception, \( E_I = \) Single fiber efficiency due to inertial impaction, \( E_D = \) Single fiber efficiency due to diffusion, \( E_E = \) Single fiber efficiency due to electrostatic charge.
efficiency due to electrostatic charges on fibers and $E_G$ = Single fiber efficiency due to gravity.

2.13.3.1 Direct Interception

Particle capture by interception occurs when the particles follow the airflow streamline, and because of its size, it comes into contact with the fiber (Figure 2.6). Particles $>0.1$ µm get captured by this mechanism. For the Kuwabara model, the single fiber efficiency due to interception is given by [77]

$$E_R = \frac{1}{2Ku} \left\{ 2(1 + N_R) \ln(1 + N_R) - (1 + N_R)(1 - c) + (1 + N_R)^{-1} \left( 1 - \frac{c}{2} - \frac{c}{2}(1 + N_R)^2 \right) \right\}$$

Where: $N_R = \frac{d_p}{d_f}$ = Dimensionless parameter describing capture by interception, $d_p =$ diameter of the particle

![Figure 2.6 Capture mechanism due to direct interception.](image)

When nanofibers are considered, aerodynamic slip should be taken into account. Therefore, single fiber efficiency due to interception including the slip expression for a low packing fraction limit is given by [77]
Single fiber efficiency due to interception is enhanced taking into account for aerodynamic slip effect.

2.13.3.2 Inertial impaction

Impaction occurs, when the particle deviates from the airflow streamline because of its inertia and collides with a fiber (Figure 2.7). This mechanism is significant for particles greater than 1 µm.

![Figure 2.7 Capture mechanism due to inertial impaction.](image)

Capture efficiency by inertial impaction is related to Stokes number because it describes the behavior of particle of finite inertia in a stationary medium. Single fiber efficiency by inertial impaction based on Kuwabara model is given by [78]

\[
E_I = \frac{Stk \cdot J}{2Ku^2} \tag{2.9a}
\]

Where: Stk = Stokes number

\[
J = \text{constant} = (29.6 - 28c^{0.62})N_R - 27.5N_R^{2.8} \tag{2.9b}
\]
The Equation 2.9b for J is valid for $N_R < 0.4$ and $0.0035 < c < 0.111$ for the Kuwabara model.

\[
\text{Stk} = \frac{C_n d_p \rho U}{18 \eta d_f} \tag{2.10}
\]

where: $d_p$ = diameter of particle, $C_n$ = Cunningham correction factor

\[
C_n = 1 + \frac{2A\lambda}{d_p} + \frac{2Q\lambda}{d_p} \exp\left( -\frac{Bd_p}{2\lambda} \right) \quad \text{A} = 1.246, \text{Q} = 0.42 \text{ and B} = 0.87. \tag{2.11}
\]

The Cunningham correction factor is taken into account for calculating single fiber efficiency due to impaction for nanofibers due to the aerodynamic slip condition. The capture efficiency increases with increase in Stokes number but approaches unity asymptotically when the Stokes number is large [79].

2.13.3.3 Brownian diffusion

Diffusion occurs when small particles less than 0.1 µm deviates from airflow streamline due to the random motion of particles which causes the particles to get captured on fibers (Figure 2.8).

Figure 2.8 Capture mechanism due to Brownian diffusion.
The single fiber efficiency by Brownian diffusion based on Kuwabara model is given by [79]

$$E_d = 1.6 \left( \frac{1 - c}{Ku} \right)^{\frac{1}{3}} Pe^{-\frac{2}{3}}$$

(2.12)

where $Pe = \text{Peclet number} = \frac{Ud_f}{D}$, $D = \text{diffusion coefficient} = \frac{C_a K_B T}{3 \pi \eta d_p}$,

$K_B = \text{Boltzmann’s constant} = 1.38 \times 10^{-23} \text{ m}^2 \text{ Kg s}^{-2} \text{ K}^{-1}$, and $T = \text{temperature}$.

The slip flow effect is taken into account for nanofibers and capture efficiency due to diffusion is given as [80]

$$E_d = 1.6 \left( \frac{1 - c}{Ku} \right)^{\frac{1}{3}} Pe^{-\frac{2}{3}} C_1 C_2$$

(2.13)

$$C_1 = 1 + 0.388 Kn \left( \frac{1 - c}{Ku} \right)^{\frac{1}{3}}$$

(2.14)

$$C_2 = \frac{1}{1 + 1.6 \left( \frac{1 - c}{Ku} \right)^{\frac{1}{3}} Pe^{-\frac{2}{3}} C_1}$$

(2.15)

Equation [2.13] is of good agreement for particle size in the range of 0.08 – 0.4 μm. The Peclet number gives the value relating the relative magnitude of diffusional motion and the convective motion of the air past the fiber. Therefore, the capture efficiency by diffusion will increase as Peclet number decreases.

2.13.3.4 Electrostatic mechanism

Particle capture due to electrostatic mechanism is very rare phenomenon in mechanical filtration [81]. After the fiber contact is made, small particles are retained on the fibers by a weak electrostatic force (Figure 2.9). Capture efficiency by electrostatic
mechanism can significantly increase the filtration efficiency without any pressure drop increase. It is significantly useful for enhancing the capture efficiency of the particles in the size range of 0.15 – 0.5 µm [82].

Figure 2.9 Capture mechanism due to electrostatic mechanism.

The two primary methods of applying electrostatic forces to increase the collection efficiency of a filter is by charging the airborne particles and creating an electric field in the filter. In the first method, electrically charged particle polarizes the fiber and as a result experiences a force between charged particle and a neutral fiber called as an image force. The dimensionless parameter describing the particle capture by image forces is given by [75]

\[
N_{0q} = \frac{D_f - 1}{D_f + 1} \frac{q^2 C_o}{12 \pi^2 \eta U \varepsilon_o d \mu d_f^2}
\]

(2.16)

where: \(D_f\) = Dielectric constant of fiber material, \(q\) = charge held by a particle, \(\varepsilon_o\) = permittivity of free space, \(N_{0q}\) = dimensionless parameter describing capture of charged particles by a neutral fiber.
The following expression was derived based on the experimental result to calculate the single fiber efficiency based on image force is given by [83]

\[ E_{\text{eq}} = 1.5N_{\text{eq}}^{0.5} \]  \hspace{1cm} (2.17)

Where: \( E_{\text{eq}} = \) Single fiber efficiency by neutral fiber with charged particle

The above Equation 2.17 holds good with experimental results for micron and submicron particle size and using neutralized glass fiber filter.

In the second method, an external electric field is applied to polarize the fiber as well as the particles. The dimensionless parameter (\( N_{\text{eq}} \)) describing the capture by multipole charged fiber on charged particle is given by [75]

\[ N_{\text{eq}} = \frac{\sigma qC_n}{3\pi \eta(1 + D_f)Ue_0d_p} \]  \hspace{1cm} (2.18)

Single fiber efficiency based on Kuwabara model for capture of charged particle on charged fiber (\( E_{\text{eq}} \)) for packing fraction of 0.05 and dimensionless parameter (\( N_{\text{eq}} \)) ranging between 0.1 and 10.0 is given by [75]

\[ E_{\text{eq}} = 0.59Ku^{-0.17}N_{\text{eq}}^{0.83} \]  \hspace{1cm} (2.19)

The Cunningham slip factor is taken into account to calculate the single fiber efficiency based on electrostatic forces for fiber diameter in the scale of nanofibers.

2.13.3.5 Gravitational settling

Gravitational settling occurs, when the heavy particles settle down on the fiber under the influence of gravity.

2.13.4 Relative importance of bounce and re-entrainment

The single fiber efficiency approach is based on the assumption that all fibers are identical in the filter which is not true in the real filter. Another assumption is that capture mechanism acts alone but in real situation several mechanism acts together. Single fiber
theory is described based on the assumption that particles adhere to fibers on contact but ruled out the possibility of particle bouncing away from the fiber after impact. As a particle strikes the fiber the dissipation of particle’s kinetic energy and particle bouncing depends on whether the collision has sufficient kinetic energy after impact to escape from the fiber.

Particle detachments are more likely to occur at the point of impact and therefore, captured particles are unlikely to be re-entrained by the airflow from which they were captured unless external forces overcome attractive forces between dust particles and fibers [75]. The re-entrainment of captured particles will occur under conditions such as high Stokes number (high particle velocity and mass), fibers are heavily dust loaded (aerodynamic drag force increases with dust loading) and different modes of vibration aid in removing the captured particles [72, 75]. Capture by inertial impaction has a higher chance of particles leaving the fiber surface than interception because particle’s velocities are larger for inertial impaction [75]. The adhesion and rebound of particles are more significantly affected by the surface properties than the material properties of fibers [84]. Thus, collection efficiency is lower than collision efficiency, which assumes that particles that are captured adhere to the fiber.

Three primary forces that contribute to the adhesion of dust particles to the fiber are Van der Waals, surface tension and electrostatic forces. Van der Waals adhesive force predominates for small particles while the electrostatic adhesive forces have an influence on particle attachment for large particles [84]. Surface tension forces come into play, when the water vapor may condense in the gap between dust particles and a fiber. Capillary forces between dust particle and fiber dominates at relatively high humidities
while Van der Waals forces are significant in dry environments [84]. Adhesion of captured particles to the fiber is greater at higher air velocities because of surface deformation but efficiency decreases because more particles may bounce back at higher velocity. The particle bouncing probability does not only depend on adhesion between particle and a fiber but also on the factors such as contact area between particle and fiber, mechanical properties of fibers, particle shape, surface roughness of the particle, relative humidity and angle and velocity of impact [75]. It is reported that it is easier to detach particles from thicker fibers than from thin ones [85]. Thus, in the case of nanofiber filter media, the probability of detachment is less than with larger fibers once the particles are captured.

2.13.5 Effect of loading

The captured particles becomes the integral part of filter and contribute both to pressure drop and filtration efficiency. Particle deposition is most effective in the initial layers of the filter and as deposition rate proceeds, there is a tendency to convert from depth filtration to surface filtration. This behavior is considered to be final behavior regime of clogged fibrous filter. Clogging is a time dependent process and its rate is influenced by the aerosol and filter properties [75]. Fine dust causes both the resistance as well as filtration efficiency to increase whereas the coarse dust has a very little impact on both resistances as well as on the filter efficiency [86].

Lot of work has been done to predict the performance of the filter media loaded with particles. Collection efficiency of single fiber loaded with particles for isolated fibers as well as for an array of parallel fibers is given by [87]
Where, \( \eta \) = collection efficiency of single fibers, \( \eta_0 \) = initial efficiency, \( b \) and \( c \) are empirical fit coefficients.

The authors proposed a dendrite growth model in which collected particles results in the formation of particle dendrites and acts as an additional fiber collectors and contributes towards particles collection and pressure drop across the filtrer media [88]. In the model, collected particles as dendrites are assumed to be secondary fibers of particle diameter [88]. One of the assumptions is there is no interaction between fibers and dendrites and total pressure drop across the filter media is the sum of the pressure drop across the fibers and pressure drop across dendrites with packing density [88]. The packing density of dendrites is based on the parameters such as loading time, velocity, concentration of particles, porosity of the media, etc. Similar approach is used to determine the mass of particle collected by the media which is the sum of particle collected by the fibers and by the dendrites of particle diameter.

2.14 Media properties of nanofiber filter media

Media physical properties like fiber diameter, porosity, basis weight of nanofibers over a substrate, different types of substrate, media uniformity affects the performance of filter in the air filtration process.

2.14.1 Fiber diameter

Fiber diameter influences the particle capture efficiency. As the fiber diameter is decreased, surface area over volume increases which benefits us in more particle capture
by the fiber. It is reported that efficiency increases by a factor of 2000, when a 50 µm fiber diameter is replaced by a 1 µm due to the increased surface area [89].

2.14.2 Porosity

Fibrous filters are usually highly porous. Porosity and pore size distribution affects the particle capture and pressure drop across the filter. Mean fiber diameter of spunbonded substrate and nanofiber are 13 µm and 0.2 µm. Table 2.7 gives the comparison of average pore diameter, least and biggest pore diameter for spunbonded and nanofibers.

Table 2.7 Pore diameter distribution of spunbonded substrate and nanofibers

<table>
<thead>
<tr>
<th></th>
<th>Spunbonded fibers (µm)</th>
<th>Nanofibers (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. pore diameter</td>
<td>41.99</td>
<td>0.74</td>
</tr>
<tr>
<td>Least pore diameter</td>
<td>18.06</td>
<td>0.6</td>
</tr>
<tr>
<td>Biggest pore diameter</td>
<td>96.4</td>
<td>1.73</td>
</tr>
</tbody>
</table>

When the nanofibers were used, the average pore diameter reduced from 41.99 to 0.74 µm compared to micron sized fiber. Since the pore diameters are much smaller in nanofibers, particles are captured much easier than micron sized fiber [90].

2.14.3 Basis Weight of nanofibers on a substrate

Basis weight of nanofibers is the amount of nanofibers per unit area of substrate. Electrospun nanofiber web of basis weight in the range of 0.02 – 0.5 g/m² were spun on cellulose substrate [91]. It is reported that composite media comprising of nanofibers of 250 nm over a cellulose substrate of fiber diameter exceeding 10 micron is holding 2.5
times more dust than cellulose media [92]. The above experiment was carried out by loading both the media to the same pressure drop of 0.5 inches of water with ISO fine test dust in the size range of 0.7 – 70 microns. The significant quantity of submicron particles were captured at the nanofiber surface of composite media compared to relatively few submicron particles captured on the cellulose sample [92]. Increase in dirt holding capacity of nanofiber filter media is due to the increased surface area of the fibers due to small fiber diameter.

2.14.4 Role of substrate

Nanofibers have been laid over various substrates based on various applications such as cellulose, spunbonded, meltblown and on various textile surfaces such as nonwoven, knitted, woven and charmeuse substrate [93]. Nanofibers of mean fiber diameter of 0.2 µm were laid over meltblown substrate of mean fiber diameter of 4 µm and spunbonded substrate of mean fiber diameter of 13 µm. Both the filtration efficiency and pressure drop across the filter media varies based on substrate properties even though same Poly (vinyl alcohol) (PVA) nanofibers were spun over two substrates.

The role of substrate in nanofiber filter media is that the substrate should have good mechanical properties to provide nanofibers a good structural support for filter fabrication and durability in use. In most cases, conventional filter media which have been used for particular applications are selected as substrate because of advantage of using conventional media pleating equipment for filter fabrication [94].
2.15 Filters for hot gas filtration

In today’s Process and Power Industries, temperatures of dust laden hot gases are well above 1000° C. Economically, it would be convenient to use high energy potential of hot waste gases in recovery boilers for producing electricity [12]. However, dust contained in hot gases results in a rapid failure of any heat recuperators. In practice, two types of equipment are used to clean waste gases from the dust are bag filters and electric filters. The gases need to be cooled before they are transferred to this equipment, since bag filters and electric filters cannot operate at high temperature [95]. The cooled cleaned gases have low enthalpy and use of any recuperators for recovering heat from these gases becomes economically ineffective.

2.15.1 Heat loss in various industrial processes

The increasing consumption of energy in the last few decades has increased the toxic impact on the environment. Discharge of the polluting agents varies depending on the type of power plant and fuel used [95]. Technological processes in metallurgical, chemical, gas and oil and thermal plants leads to the increase in dust laden emissions of hot exit gases at temperature as high as 1000° C (Table 2.8) [95]. Analysis of Table 2.8 suggests that heat losses via hot waste gases amount to 60%, that is, up to 60% fuel combustion heat is spent on heating ambient air. Thus, cleaning waste gases can be used to recover their substantial heat for producing electricity.
2.15.2 Dust collecting devices for hot gas cleaning

Filters are more efficient for trapping micron particles compared to other dust cleaning devices used for gas cleaning (Table 2.9) [95]. However, these filter devices require cooling of gases since filter materials cannot withstand high temperatures. Glass fabrics can withstand temperatures up to 250°C. Two methods for cooling hot gases are used in industrial practice. First method employs evaporative cooling of hot gases by circulating water onto hot gases. Second method is by cooling the hot gas by diluting it with cold air. Both methods are expensive because the former method requires lot of water for circulation and the latter needs a large volume of air. It would be beneficial from economic point of view to filter out hot gases without reducing their temperature to eliminate the need for cooling systems as well as using thermal energy of the gas for producing electricity.

<table>
<thead>
<tr>
<th>Process, furnace</th>
<th>Waste gas temperature, °C</th>
<th>Dust content in waste gases, g/m³</th>
<th>Heat loss via waste gases, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig iron production</td>
<td>800</td>
<td>40-50</td>
<td>35-45</td>
</tr>
<tr>
<td>Steel production</td>
<td>1000</td>
<td>30-70</td>
<td>50-60</td>
</tr>
<tr>
<td>Copper production</td>
<td>800</td>
<td>15-20</td>
<td>30-35</td>
</tr>
</tbody>
</table>
Table 2.9 Dust collecting devices for hot gas cleaning [95].

<table>
<thead>
<tr>
<th>Dust collecting device</th>
<th>Size of captured particles, μm</th>
<th>Efficiency of collecting dust particles of different sizes, %</th>
<th>Upper temperature limit of purified gas, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling chamber</td>
<td>40 – 1000</td>
<td>80 – 90</td>
<td>Up to 350</td>
</tr>
<tr>
<td>Cyclone</td>
<td>20 – 1000</td>
<td>50 – 80</td>
<td>Up to 350</td>
</tr>
<tr>
<td>Scrubber</td>
<td>20 – 100</td>
<td>80 – 90</td>
<td>Up to 350</td>
</tr>
<tr>
<td>Electric filter</td>
<td>0.05 – 10</td>
<td>90 – 95</td>
<td>Up to 350</td>
</tr>
<tr>
<td>Filter</td>
<td>0.05 – 100</td>
<td>98 – 99</td>
<td>Up to 250</td>
</tr>
</tbody>
</table>

2.16 Available technologies for high temperature filters

2.16.1 Candle filters

Filter vessels consist of a desired number of candle filters to filter out particles from the hot gases above 850°C. Dusty gas enters the filter unit and particulates collect on the surface of the candle filters. Particulates form a dense cake on the wall of the filter and pressure drop across the filter element increases. A high pressure air is injected into the filter element to dislodge the filter cake. Porous permeable ceramic materials are used to fabricate candle filters.

2.16.2 Porous permeable ceramic materials

Pore structure such as size, volume and shape and filter thickness are responsible for filtration efficiency, pressure drop and materials strength. These ceramic materials, with controlled pore size and shape can be made up from sintered powder, fibers or celled foams [96]. Powder based permeable materials have an porosity of 20 – 45% with pore size of 5 – 400 μm whereas fiber based material have porosity of 30 – 90% with pore size
5 – 200 μm [12]. Filter element made up of inorganic fibers which can filter out particles at temperature 1000°C [95].

2.16.3 Monolith ceramics

Monolith filters consist of uniform pores and are aligned in the direction of the thickness of the filter. They are available in many forms and most common form is honey the comb structure. Monolith ceramics are usually made up of materials such as silicon carbides and metal oxide elements such as alumina. Monolith ceramics made of Silicon carbide and metal oxide elements were tested at temperatures above 850°C [97]. Filter elements made of silicon carbide is oxidized by the steam present in flue gas and causes macro and micro cracking with subsequent strength reduction whereas metal oxide filter element have good strength properties and good thermal resistant at temperatures over 900°C [97]. Monolith ceramics are brittle while handling [97].

2.16.4 Sintered metals

Filters are made of sintered metal particles or fibers almost resembling similar porous structures as fabricated from ceramic materials. Sintered iron aluminide is used to fabricate sintered metal filters [97]. Advantages of using sintered materials are high strength and good thermal shock resistance. They do not have corrosion stability at high temperature [96, 97].

2.16.5 Granular filters

Granular filters are surface filters consisting of a coarse grain support structure covered with a fine grain surface to restrict particles penetrating into the body and are trapped on the wall of the filters. Granular filters are used for hot gas clean up for advanced coal conversion technologies [98].
2.16.6 Ceramic fibrous filters

Ceramic fiber filters consist of ceramic fibers which are bonded together by ceramic binders. Ceramics fibers are produced by melt spinning process, wherein a ceramic thermoplastic polymer is forced by spin pumps to form continuous polymer fibers. These fibers are calcined at high temperatures to produce ceramic fibers. Ceramic microfibers have diameters in the range of 2-8 µm. Ceramic fibrous filters are highly porous and are highly permeable.

2.16.7 Advantages and technological importance of the ceramic fibrous filters

Some of the important requirements that filters needs to meet for hot gas filtration are

1. Sufficient mechanical strength to withstand operating environment
2. Chemical inertness
3. high permeability for gas flow
4. Good recovery from the thermal shocks and thermal fatigue
5. Longevity of filter

Dust collector devices such as scrubbers, cyclones, and settling chambers cannot perform at elevated temperatures. The mechanical strength of membrane filters and properties of electrostatic filters are dubitable at elevated temperatures. Granular and monolith filters are more efficient in capturing particles in the range of 10 microns and above. It is known that microfiber filters can capture the fine particles efficiently at low pressure drops [99]. The greatest advantage of using ceramic fibrous filters is that they can withstand high temperatures ~ 1200°C and can capture fine particles.
2.16.8 Ceramic fibrous filter

After reviewing several literatures, the various possible binders and ceramic fibers which can be used for hot gas filtration are tabulated in Table 2.10

Table 2.10 Comparison chart of possible materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Binders</th>
<th>Operating Temperature during filtration (°C)</th>
<th>Reference Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina fibers</td>
<td>Not specified</td>
<td>800 – 1000</td>
<td>100</td>
</tr>
<tr>
<td>Polycrystalline metal oxide fibers</td>
<td>Not specified</td>
<td>Above 1100</td>
<td>101</td>
</tr>
<tr>
<td>Alumino silicate fibers</td>
<td>Silica or alumina binders</td>
<td>750 – 950</td>
<td>102</td>
</tr>
<tr>
<td>Mullite – aluminium titanate fibers</td>
<td>Methyl cellulose is used as an organic binder</td>
<td>1650 – 1700</td>
<td>103</td>
</tr>
<tr>
<td>Amorphous silicon oxynitride fibers</td>
<td>Not specified</td>
<td>1200</td>
<td>104</td>
</tr>
<tr>
<td>Silicon carbide powders</td>
<td>Clay based binders</td>
<td>1000</td>
<td>105</td>
</tr>
<tr>
<td>SiC grains</td>
<td>Clay based binder containing alkali and aluminosilicates</td>
<td>870</td>
<td>106</td>
</tr>
<tr>
<td>Alumina fiber</td>
<td>colloidal silica, colloidal alumina and monoaluminium phosphate binder</td>
<td>Not stated but indicated as for high temperature</td>
<td>107</td>
</tr>
<tr>
<td>Continuous alumina fiber reinforced mullite composites</td>
<td>TEOS (Tetraethoxysilane )</td>
<td>400</td>
<td>108</td>
</tr>
<tr>
<td>Silicate fiber</td>
<td>Clay, polyvinyl alcohol as temporary binder</td>
<td>800</td>
<td>109</td>
</tr>
</tbody>
</table>

2.17 Potential application of Ceramic nanofibers for hot gas filtration

Our main focus is on understanding the nanofiber filter media for specific application area such as process and power industries. In today’s process and power
industries, temperatures of dust laden hot gases are well above 1000° C. However, dust contained in hot gases results in a rapid failure of any heat recuperators. In order to protect the turbine and recuperators from dust induced damage, the hot gases need to be filtered to remove submicron particles. The addition of nanofibers to microfiber filter media will improve the capture efficiency of submicron particles. Thus, ceramic nanofibers can be added to microfiber filter media, which can withstand high temperature as well as capture submicron particles of hot gases. In our research work, ceramic nanofibers were fabricated. Ceramic nanofiber filter media comprising of microfibers and nanofibers were developed and can find potential applications in non-ferrous, ferrous, coal, cement, quarry, waste incineration, pressurized fluidized bed combustion, coal power plants, flue gas desulphurization, industrial fumes, diesel engine exhausts and cleaning of hot exit gases. Development of ceramic nanofiber filter media for high temperature applications is still quite unique and challenging. [110-111]. The application of ceramic nanofiber filter media for hot gas filtration is expected to be cost effective because of removal of cooling towers, thermal energy of hot waste gases can be used for producing electricity and high turbine efficiency results, if the inlet of the gas turbines are maintained at elevated temperatures and decrease in temperature results in poor performance [112].
CHAPTER III
MODELING OF COMPOSITE FILTER MEDIA

3.1 Introduction

The performance of a filter medium is measured by its pressure drop and capture efficiency. The capture efficiency of filter medium is defined as


3.1

Quality factor (QF) is a term which takes into account both capture efficiency and pressure drop of filter medium in one equation and is given by


3.2

The higher the quality factor, better the performance of the filter medium and lower the power requirement for the process for constant volumetric flow rate of gas stream (Power = ΔP*Q). QF is a measure of the separation performance per amount of energy expended to separate particles from the gas stream. Thus, QF term is used to compare the performance of different filter media.

The Relative Quality factor (RQF) is used to compare how the performance of filter medium changes with the addition of nanofibers


3.3


51
where, $QF_{base}$ is the Quality Factor of the microfiber filter medium without nanofibers as the basis of comparison. When the $RQF > 1$, nanofiber filter medium performance better than microfiber filter medium.

3.2 Objectives

The objective of this model is

1. To predict the performance of mixed micro and nanofibers filter medium
2. To determine the amount of nanofibers added to the microfiber filter medium to enhance the filter performance of clean filter medium.

3.3 Model development

A model was developed based on volume averaged continuum theory to predict the performance of mixed micro and nanofiber filter media. The model derivation is similar to that previously reported [113] but here it is applied to air filtration and high temperature gases. The gas stream with solid particles flows through the fibrous media and the particles are captured in the depth of the filter (Figure 3.1). The set of working equations derived here for this particular model represent balances on mass continuity, momentum and species balance.

Figure 3.1 The inlet gas stream enters the composite filter medium, solid particles are captured by fibers and the exit stream carries fewer particles.
Conservation equations

Gas mass balance

---

3.4

Gas momentum balance

---

3.5

Gas particle species balance

---

3.6

Solid (fiber) mass balance

---

3.7

Solid (fiber) momentum balance

---

3.8

The following assumptions are made to simplify the model equations and are listed below:

1. One dimensional flow in Z direction at the volume averaged scale ( )

2. Solid fibers are stationary

3. Captured particles are stationary on fibers ( )

4. No heterogeneous reaction generation
5. No slip transfer across the interface ()

6. No rate of mass generation of species A due to homogeneous chemical reaction ( =0)

7. Gravity term is neglected (g =0)

8. No amount of mass is transferred from the solid fibers due to phase change ( =0)

9. No mechanical transfer across the interface ()

10. The permeability of the fibrous media is uniform and isotropic

11. The media is incompressible and the process is isothermal

12. Fibers are of one fiber size

13. Particles are of one size

14. Fibers are randomly oriented

15. Effect of binder materials are neglected

16. Correlation for capture mechanism and pressure drop are based on single fiber theory

17. The captured particles do not re-entrain into the air stream

18. Effect of particle loading is not considered in this model

19. Gas face velocity is constant

Gas mass balance

---

3.9

Gas momentum balance

---

3.10

Gas particle species balance

---

3.11

Solid mass (fiber) balance
Solid momentum balance

Gas species constraint

\( I_0^G \) = mass flux of aerosol particles captured from gas phase onto fibers

The mass fraction aerosol particles in the gas phase \((w_0^G)\) is the ratios of mass concentrations of particles to the mass concentrations of gas

The gas phase momentum balance (Equation 3.10) is used to determine the pressure drop across the media. The momentum balance is solved by finding a constitutive equation for the drag force.

The gas phase mass balance (Equation 3.9) and gas particle species balance (Equation 3.11) are used to determine the aerosol outlet concentration.

At start up condition,

Equation 3.11 gives

The species balance is solved by finding a constitutive equation for the mass transfer term.
3.3.1 Constitutive equation for mass transfer term

The filter coefficient $\alpha$ is defined as

\[ 3.19 \]
\[ 3.20 \]
\[ 3.22 \]
\[ 3.23 \]

Substituting the interphase mass transfer term in gas particles species gives

\[ 3.24 \]

From Equation 3.17, Therefore,

\[ 3.25 \]
\[ 3.26 \]

On integrating equation from 0 to $L$

\[ 3.27 \]

The overall filter coefficient, $\alpha$ is related to the single fiber efficiency by

\[ 3.28 \]
\[ 3.29 \]

where $E_i$ is the capture efficiency and $\varepsilon_i$ is the volume fraction of the filter media occupied by fibers of diameter $d_i$. The model considers both microfibers and nanofibers in the filter media. Therefore, for the mixture of fibers, the filter coefficient is given by

\[ 3.30 \]
Correlations for the single fiber capture efficiencies \( E_i \) are available from single fiber theory [75]. The dominant mechanisms for submicron particle size are direct interception and Brownian diffusion. Other capture mechanisms are considered negligible in this model. Single fiber capture efficiency by diffusion and direct interception accounting for aerodynamic slip is calculated from

\[
E = \frac{DE}{1 + DE}
\]  \hspace{1cm} (3.31)

Brownian diffusion efficiency \( E_D \) is calculated from

\[
E_D = \frac{4}{3} \frac{D}{
u D}
\]  \hspace{1cm} (3.32)

Direct interception efficiency \( E_R \) is calculated from

\[
E_R = \frac{1}{2} \left( \frac{d_p}{d_f} \right)^2
\]  \hspace{1cm} (3.33)

The combination term of interception and diffusion is calculated from

\[
E = \frac{DE}{1 + DE}
\]  \hspace{1cm} (3.34)

Where \( \frac{d_p}{d_f} \) is the ratio of the diameters of the particles to the fibers,

\[
\frac{d_p}{d_f} = \frac{4}{3} \frac{
u D}{D}
\]  \hspace{1cm} (3.36)

Knudsen number \( \frac{\lambda}{d_f} \) is the ratio of the mean free path of air molecules to fiber diameter,

\[
\frac{\lambda}{d_f} = \frac{4}{3} \frac{
u D}{D}
\]  \hspace{1cm} (3.37)

The Peclet number is

\[
P_e = \frac{4}{3} \frac{\lambda}{d_f}
\]  \hspace{1cm} (3.38)
Where diffusion coefficient of the particles is given by

is the mobility given by

The constants are $A = 1.246$, $Q = 0.42$ and $B = 0.87$.

The $\lambda = 0.065 \, \mu m$ is the mean free path of air molecules at 25°C and 1 ATM pressure. The filter coefficient $\alpha$ is calculated using the above equations and hence, the outlet concentrations of particles are calculated using Equation 3.27.

3.3.2 Constitutive equation for the drag force

The gas phase momentum balance (Equation 3.10) gives

Integrating the above equation from 0 to $L$ for a filter of uniform properties gives

The pressure drop across the media is related to the total force acting on all fibers by

Total force acting on all fibers is related to force per unit length of fibers ($F/L$) by

where $L$ is the total length of fibers of diameter $d$. For the composite filter medium of microfibers and nanofibers, the medium has two fiber diameters and total pressure drop is the sum of drag force acting on microfibers and nanofibers and is given by
Substituting in Equation 3.43 gives

The length of fibers is related to the volume fraction of fibers by

Substituting into Equation 3.48 yields

The flow regimes are classified into different regimes such as continuum, slip, transition or molecular flow based on Knudsen number, which depends on fiber diameter. The correlations for depending on fiber diameter are available for continuum, slip or molecular flow in the literature. Correlations for pressure drop for media of uniform fiber [75] are used to obtain correlations for $f_i$. Rearranging Eq. 3.47 for one fiber size yields

For $Kn < 0.01$, correlation for pressure drop for continuum flow regime is

For $Kn < 0.25$, correlation for pressure drop for slip flow regime is

Thus, we get expression for (for slip flow) from pressure drop correlation of slip flow regime by substituting Equation 3.52 in Equation 3.53 gives
For $Kn>10$, correlation for pressure drop for molecular flow regime is

Hence,

These correlations (Equation 3.54 and 3.56) for different flow regimes are used to calculate the drag force acting on fibers. There is no correlation available in the literature for transition flow regime $0.25 \leq Kn \leq 10$ and is a topic of current research. In our model, we assumed a linear interpolation between slip and molecular flow to estimate the value of $\ldots$ for transition flow regime.

Substituting Equation 3.50 in Equation 3.43 yields

The Equation 3.57 is used to calculate the pressure drop across the composite filter medium.

3.4 Model results for composite filter medium at room temperature

The model is programmed into a spreadsheet for calculations. The filter is modeled at room temperature, atmospheric pressure, with air face velocity of 2.1 m/s. The filter medium is 1 cm thick and 6 cm in diameter. The porosity is determined from the volume of the fibers present in the filter medium. The amount of nanofibers in the filter medium is calculated as the ratio of the external surface of the nanofibers divided
by the external surface area of the microfibers in the filter medium. An area ratio of zero means no nanofibers are added to the filter medium. An area ratio of 0.5 means 0.03 g of nanofibers added to the 2g of microfibers in the filter medium.

Figure 3.2 shows the RQF curves for three particles sizes for 3 micron diameter microfibers and 300 nm diameter nanofibers. The RQF increases steeply with small addition of nanofibers, reaches a maximum value at an area ratio of about 1 to 2 and then decreases with further addition of nanofibers in the filter medium. The rapid increase in RQF with small addition of nanofibers is due to the significant increase in the capture efficiency with least increase in pressure drop. Higher capture efficiency is contributed by the nanofibers due to high surface area available for capture of particles. As more nanofibers are added to the filter medium, the pressure drop across the filter medium increases which is higher than capture efficiency benefits due to nanofibers. Thus, there are two competing mechanisms in terms of pressure drop and capture efficiency. By optimizing the amount of nanofibers added to the filter medium, performance of the filter medium can be enhanced. In our case, an area ratio in the range of 1 maximizes the filter performance. Figure 3.2 also shows that RQF depends on the size of the particles being captured.
Figure 3.2 Relative quality factors for different sizes of particles.

Two sizes of microfibers are compared in Figure 3.3. The fibers of 5 micron show the largest RQF among three fiber sizes with the addition of nanofibers. This is due to the large difference in the magnitude of fiber diameter. Quality factor of 3 micron fiber diameter without nanofibers performs better than 5 micron fiber diameter because of higher capture efficiency due to 1 micron than 5 micron. As the nanofibers are added, capture efficiency benefits from nanofibers are more for filter media made up of 5 micron fibers than 3 micron and RQF increases more for 5 micron as compared to 3 micron. Thus, the plot shows there are tremendous improvement for larger microfibers when nanofibers are added. The RQF for microfibers of different fiber diameter is maximum in an area ratio of 1 to 2.
The Figures 3.2 – 3.3 shows that it may be possible to enhance the performance of filter media for the capture of particular sizes by optimizing the filter design.

3.5 Development of model for a filter medium for high temperatures

The above developed model is used to predict the performance of filters at various temperatures. The model assumes the whole filter is maintained at a uniform steady temperature and filter performance parameters are predicted at that particular temperature. Mass flow rate of air is held constant and therefore, face velocity varies for different temperatures due to change in air densities. Various uniform temperatures such as 21, 500, 1000 and 1500°C are considered and filter performance parameters (pressure drop, outlet concentration and quality factor) are calculated at the corresponding temperatures. The temperature dependent properties such as gas density, mean free path of air molecules and gas viscosity are considered in this study.
3.6 Model results for fibrous filter at elevated temperature

Table 3.1 lists the model conditions for the model. Since the mass flow rate is kept constant, with rise in temperature, density of air changes leading to increased face velocity.

Table 3.1 Model conditions for various temperatures

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Air (Density, Viscosity and mean free path of air molecules vary with temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameter</td>
<td>150 nm</td>
</tr>
<tr>
<td>Fiber diameter</td>
<td></td>
</tr>
<tr>
<td>Microfibers</td>
<td>3 micron</td>
</tr>
<tr>
<td>Nanofibers</td>
<td>300 nm</td>
</tr>
<tr>
<td>Area ratio of nanofibers to microfibers</td>
<td>Variable 0 to 10. The amount of microfibers is constant. Surface area ratio is a measure of the amount of nanofibers in the medium.</td>
</tr>
<tr>
<td>Gas mass flow rate</td>
<td>7.25 g/s</td>
</tr>
<tr>
<td>Filter dimensions</td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>6 cm</td>
</tr>
<tr>
<td>Thickness</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

Figure 3.4 shows the relative quality factors of filters for different area ratios at various temperatures. In this case, the relative quality factor is defined as the ratio of quality factor of a filter medium to the quality factor of filter medium with no nanofibers at a given temperature. The RQF increases and reaches a maximum value at an area ratio of 1 to 2 and then decreases for all temperatures. The RQF for filter medium at room temperature is maximum and as temperature increases the RQF decreases. Figure 3.5 shows the plot of comparison of a composite filter medium and microfiber filter medium.
Since the filter performance is maximum for an area ratio of about 1, this plot considers comparison of microfiber filter medium and filter medium with nanofibers for an area ratio of 1. The plot shows the quality factor for a composite filter medium is higher than the microfiber filter medium for all temperature. There is a common trend of quality factor with rise in temperature of hot gases for both composite filter medium and microfiber filter medium. The decrease in quality factor is due to the increased pressure drop as temperature rises.

Figure 3.4 Relative quality factors at various temperatures.
Figure 3.5 Quality factor plot for microfiber and composite filter medium.

The Figure 3.6 shows the plot of pressure drop across the filter medium for various area ratios at different temperatures for model conditions as shown in Table 3.2.

Table 3.2 Model conditions

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Air (density, viscosity and mean free path of air molecules vary with temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameters</td>
<td>150 nm</td>
</tr>
<tr>
<td>Fiber diameters</td>
<td></td>
</tr>
<tr>
<td>Microfibers</td>
<td>3 microns</td>
</tr>
<tr>
<td>Nanofibers</td>
<td>300 nm</td>
</tr>
<tr>
<td>Area ratio of nanofibers to microfibers</td>
<td>Variable 0 to 2. The amount of microfibers is constant. Surface area ratio is a measure of the amount of nanofibers in the medium.</td>
</tr>
<tr>
<td>Gas mass flow rate</td>
<td>$2.78 \times 10^{-4}$ kg/s</td>
</tr>
<tr>
<td>Filter dimensions</td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>6 cm</td>
</tr>
<tr>
<td>Thickness</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

There is a common trend of increased pressure drop with rise in temperature due to increased face velocity for constant mass flow rate of gas, increase in viscosity of the
gas stream reducing fluid permeability, and also due to the addition of nanofibers to the filter medium. Figure 3.7 shows the highest quality factor for a fibrous filter at lower temperature than at higher temperature at all area ratios of nanofibers to microfibers for constant mass flow rate. Quality factor of the filters improves with the small addition of nanofibers for all temperatures. The highest quality factor occurs for an area ratio of nanofibers to microfibers in the range of 0.8 to 1.0 for all temperatures.

Figure 3.6 Pressure drop across the filter medium versus area ratio for various temperatures
3.7 Summary

Modeling nonwoven media with nanofibers showed a significant increase in the filter performance with the addition of small amounts of nanofibers. The relative quality factor plot pass through a maximum and gradually decreases as greater amount of nanofibers are added to the filter. The plot shows RQF dependence on the amount of fibers, fiber size and particle size and by optimizing the filter design, we can enhance the performance of the filter media. The model is done to show the performance trend of fibrous filter for varying ratio of nanofibers at elevated temperature. The quality factor of a fibrous filter is highest for low temperature than at elevated temperature and highest quality factor occurs with an area ratio of 0.8 to 1.0 at elevated temperature.
NOTATION

\( A = \text{Area of filter media} \)

\( Cn = \text{Cunningham factor} \)

\( D = \text{Coefficient of diffusion} \)

\( d_i = \text{diameter} \)

\( g = \text{Acceleration due to gravity} \)

\( = \text{particle diameter} \)

\( E_i = \text{Single fiber efficiency} \)

\( E_R, E_D, E_{DR} = \text{Single fiber efficiencies by direct interception, diffusion, and combined diffusion and interception mechanisms} \)

\( = \text{Drag force of fiber in Z direction} \)

\( F_{tot} = \text{Total force acting on the filter} \)

\( f_i = \text{Drag force per unit length of fiber of diameter} \ d_i \)

\( Kn = \text{Knudsen number} \)

\( = \text{Boltzmann’s constant, } 1.38066 \times 10^{-23} \text{ J/}^\circ\text{K} \)

\( L = \text{Filter thickness} \)

\( L_i = \text{Total length of fibers of diameter} \ d_i \text{ within elemental volume of the filter medium} \)

\( N_R = \text{Ratio of diameters,} \ d_p / d_i \)

\( P, \Delta P = \text{Gas phase pressure, pressure drop across filter} \)
\[ Pe = \text{Peclet number} \]

\[ QF = \text{Quality Factor} \]

\[ RQF = \text{Relative quality factor (QF of the medium/QF of medium of only microfibers)} \]

\[ v_{z}^{G} = \text{intrinsic gas phase velocity in the z direction} \]

\[ G = \text{Transport of property } \varphi \text{ across an interphase boundary due to heterogeneous reaction} \]

\[ S = \text{Transport of property } \varphi \text{ across an interphase boundary due to interfacial curvature} \]

\[ E = \text{Convective transport of property } \varphi \text{ across an interphase boundary} \]

\[ I = \text{Mechanical flux of property } \varphi \text{ across an interphase boundary} \]

\[ w_{0}^{G} = \text{Mass fraction of aerosol particles in the gas phase} \]

\[ w_{in}, w_{out} = \text{Inlet and outlet mass fractions of particles in gas phase} \]

\[ \alpha = \text{Overall Filter Coefficient for the filter medium} \]

\[ \alpha_{i} = \text{Filter Coefficient of a 100\% efficient fiber} \]

\[ = \text{porosity of the media} \]

\[ = \text{Solidity of the media} \]

\[ \zeta' = \text{Hydrodynamic factor} \]

\[ \lambda = \text{mean free path of air molecules (0.065 \mu m at 25^\circ C and 1 ATM pressure)} \]

\[ \eta = \text{particle mobility} \]

\[ \mu = \text{viscosity of gas phase} \]
\( \rho = \) density

\( t = \) time

\( \rho = \) mass concentration of aerosol particles in the gas phase, kg/m\(^3\)

\( \dot{v} = \) Velocity of the fiber in Z direction

\( T = \) Temperature

Superscript

\( G = \) Gas phase

\( S = \) Solid (fiber) phase

Subscript

\( i = \) fiber

\( p = \) particle

\( Z = \) Z- direction

\( o = \) region property (property summed over all phases)

\( A = \) Species
In this chapter a model is developed to predict the effects of particle loading filter performance. Particle loading is expected to affect the pressure drop and the capture efficiency of particle onto fibers. The model requires assumptions to make the set of equations tractable, hence the predicted performance will not precisely match experimental observations but should give insight into how particle loading changes the internal structure of the filter medium and how it affects the performance. One of the ways the particle loading affects the filter performance is through the growth of dendrites, ie small fiber like structures made up of captured particles. A mechanism for dendrite growth is incorporated into the model to account for the size of the dendrites as a function of the amount of captured particles. The mechanism by which the dendrites grow in real filters are not well understood hence the mechanism used in this model is tentative.

4.1 Objectives

1. To predict trend in pressure drop and capture efficiency of the filter medium when loaded with solid particles

2. To predict the performance of fibrous filter medium for parameters such as loading time, velocity and concentration of particles.
4.2 Model development

A model was developed based on volume averaged continuum theory to predict the performance of fibrous filter when loaded with solid particles. The model considers the effect of accumulated solid particles in the fibrous media on capture efficiency and pressure drop across the media using correlations from the literature [75]. Earlier work shows that deposited particles inside the filter media forms dendrites and particles are heavily loaded in the front of the media [88]. Scanning electron micrographs of the loaded filter surface shows that filter surface are loaded with particles with the increase in loading time [88]. The test filter surfaces became completely clogged with particles after exposed to 33 minutes [88]. The effect of particle loading on the filter performance is divided in two stages. During the first stage, particles are loaded on the filter surface as well as within the depth of the media. Continuous exposure to particle loading clogs the filter surface and results in cake formation on the surface of fibrous media that is described as the second stage. In our model, we are interested in first stage to predict the performance of filter medium loaded with solid particles along the depth of the medium. The clogging of a filter medium depends on parameters such as the velocity of the gas stream, medium properties, particle size distribution, concentration of particles and loading time.

The gas stream with solid particles flows through the fibrous medium and the particles are captured in the depth of the filter (Figure 4.1). The gas phase is assumed to be air and the solid phases are the fibers and particles.
Figure 4.1 The inlet gas stream enters the microfibrous filter medium, solid particles are captured by fibers and the exit stream carries fewer particles.

The model assumes the captured particles to form dendrites on the fibers, which act as new fibers that themselves subsequently capture the particles. The set of working equations derived here for this particular model represent balances on mass continuity, momentum and species balance. The thermal energy balance is not needed since the process is isothermal.

The general volume averaged conservation equations for flows through porous media are

Gas mass balance

\[ 4.1 \]

Gas momentum balance

\[ 4.2 \]
Gas particle species balance

—

4.3

Solid (fiber) mass balance

—

4.4

Solid (fiber) momentum balance

—

4.5

Solid (particle) mass balance

—

4.6

Solid (particle) momentum balance

—

4.7

The following assumptions are made to simplify the model equations and are listed below:

1. Flow is constant and one dimensional flow in Z direction at the volume averaged scale ( )
2. Solid fibers are stationary
3. Captured particles are stationary on fibers ( )
4. No heterogeneous reaction generation
5. No slip transfer across the interface

6. No rate of mass generation of species A due to homogeneous chemical reaction

7. Gravity term is neglected (g =0)

8. No amount of mass is transferred from the solid fibers due to phase change

9. No mechanical transfer across the interface

10. The permeability of the fibrous media is uniform and isotropic

11. The media is incompressible and the process is isothermal

12. Fibers are of one fiber size

13. Particles are of one size

14. Fibers are randomly oriented

15. Effect of binder materials are neglected

16. Correlation for capture mechanism and pressure drop are based on single fiber theory

17. The captured particles do not re-entrain into the air stream

18. Collected particles are collected in the form of dendrites

19. Diameter of dendrites is equal to the twice the diameter of particles

20. Gas face velocity is constant

Applying the above assumptions, the conservation equations simplify to

Gas mass balance

— — 4.8
Gas momentum balance

—

4.9

Gas particle species balance

—

4.10

Solid (particle) mass balance

—

4.11

Solid (particle) momentum balance

—

4.12

Solid (fiber) mass balance

—

4.13

Solid (fiber) momentum balance

—

4.14

Constraints on the excess terms are necessary to ensure the sum of the species balances of a particular phase yields the phase mass continuity equation, and the sum of conservation equations over all of phases yields a conservation equation that is equivalent in form to the corresponding conservation equation for a single phase systems. The gas phase species balance constraint is

4.15

which simplifies to

4.16

The constraint on the mass balance is

0

4.17
which simplifies to

Here the interphase transfer quantities are

\[ I_0^g = \text{mass flux of aerosol particles captured from gas phase onto fibers} \]

\[ = \text{Amount of mass is transferred from gas phase onto fibers} \]

\[ = \text{Amount of mass is transferred from particle phase onto fibers.} \]

The gas phase species balance (Equation 4.10) is used to determine the outlet concentration of particles exiting the filter. The mass fraction of aerosol particles in the gas phase \( w_0^g \) is the ratio of the mass concentration of particles to the mass density of the gas phase

\[ \frac{\text{mass of particles}}{\text{mass density of gas phase}} \]

The species balance, Equation 4.10, requires a constitutive equation for the mass transfer term before it can be solved.

Similarly, the gas phase momentum balance (Equation 4.9) is used to determine the pressure drop across the media. The momentum balance requires a constitutive equation for the drag force before the equation can be solved.

Initially, at start up, the filter has no particles captured, the filter has uniform properties, and the gas within the filter does not have particles. This condition leads to,

\[ \text{—} \]

\[ \text{—} \]


4.2.1 Constitutive equation for mass transfer term

The filter coefficient $\alpha$ is defined as

\begin{equation}
\tag{4.22}
\end{equation}

\begin{equation}
\tag{4.23}
\end{equation}

\begin{equation}
\tag{4.24}
\end{equation}

\begin{equation}
\tag{4.25}
\end{equation}

Substituting Equation 4.25 in Equation 4.10 gives

\begin{equation}
\tag{4.26}
\end{equation}

From Equation 4.21

Therefore,

\begin{equation}
\tag{4.27}
\end{equation}

The overall filter coefficient, $\alpha$ is related to the single fiber efficiency by

\begin{equation}
\tag{4.28}
\end{equation}

\begin{equation}
\tag{4.29}
\end{equation}

where $E_i$ is the capture efficiency and $\varepsilon_i$ is the volume fraction of the filter media occupied by fibers of diameter $d_i$.

Model assumes that total capture efficiency of filter media is the sum of the capture efficiency due to fibers and particles are collected as dendrites and acts as additional fibers of twice particle diameter. Therefore, the filter coefficient of the filter media ($\alpha$) is the sum of capture efficiency by fibers and dendrites and is given by
\[ \frac{4}{\pi} + \frac{4}{\pi} \]

and represents the capture efficiency of fibers and dendrites. Correlations for the single fiber capture efficiencies (\( E_i \)) are available from single fiber theory and these correlations were used to determine the capture efficiency of fibers and dendrites. The dominant mechanisms for submicron particle size are direct interception and Brownian diffusion. Other capture mechanisms are considered negligible in this model. Single fiber capture efficiency by diffusion and direct interception accounting for aerodynamic slip is calculated from

\[ 4.31 \]

Brownian diffusion efficiency (\( E_D \)) is calculated from

\[ 4.32 \]

\[ 4.33 \]

Direct interception efficiency (\( E_R \)) is calculated from

\[ 4.34 \]

The combination term of interception and diffusion is calculated from

\[ 4.35 \]

Where \( \epsilon \) is the ratio of the diameters of the particles to the fibers,
Knudsen number is the ratio of the mean free path of air molecules to fiber diameter,

\[ \text{4.37} \]

The Peclet number is

\[ \text{4.38} \]

Where diffusion coefficient of the particles is given by

\[ \text{4.39} \]

is the mobility given by

\[ \text{4.40} \]

\[ \text{4.41} \]

The constants are \( A = 1.246, Q = 0.42 \) and \( B = 0.87 \).

The \( \lambda = 0.065 \) \( \mu \)m is the mean free path of air molecules at 25°C and 1 ATM pressure. Filter coefficient \( \alpha \) is calculated using the above equations. The outlet concentration of particles are calculated using Equation 4.26.

4.2.2 Constitutive equation for the drag force

Similar approach is used to calculate the pressure drop across the fiber media as that of calculating capture efficiency. Total pressure drop across the media is considered as sum of the pressure drop across the fibers and dendrites.
The pressure drop across the media is related to the total force acting on all fibers by

Total force acting on all fibers is related to force per unit length of fibers by

Where is the total length of fibers of diameter . In our model, the drag force is contributed by microfibers and dendrites. The total pressure drop is the sum of drag force acting on microfibers and dendrites and is given by

Substituting in Equation 3.43 gives

Length of fibers is related to the volume fraction of fibers by

The length of dendrites is calculated based on the Equation 4.47 (b) and is related to the volume fraction of particle collected in the filter media. Volume fraction of the media is the sum of volume fraction due to fibers and dendrites. Equation 4.11 calculates how the volume fraction of particles changes with respect to time. By calculating for small time steps and substituting in equation 4.47 b provided us the length of the dendrites.

Substituting in Equation 4.46 yields
The flow regimes are classified into different regimes such as continuum, slip, transition or molecular flow based on Knudsen number, which depends on fiber diameter. The correlations for depending on fiber diameter are available for continuum, slip or molecular flow in the literature. There are no general correlations available in the literature for the transition flow regime $0.25 \leq Kn \leq 10$. In our model, we assumed a linear interpolation between slip and molecular flow to estimate the value of for the transition flow regime.

For $Kn < 0.01$, correlation for pressure drop for continuum flow regime is

$$\text{expression}$$

For $Kn < 0.25$, correlation for pressure drop for slip flow regime is

$$\text{expression}$$

Rearranging Eq. 4.45 for one fiber size yields

$$\text{expression}$$

Thus, we get expression for (for slip flow) from the pressure drop correlation for the slip flow regime by substituting Equation 4.50 in Equation 4.51, which gives

$$\text{expression}$$

For $Kn > 10$, correlation for pressure drop for molecular flow regime is

$$\text{expression}$$

Hence,
These equations (Equation 4.52 and 4.54) for different flow regimes are used to calculate the drag force acting on microfibers and dendrites.

Substitution of Equation 4.48 in Equation 4.9 yields

\[
- \quad - \quad -
\]

The Euler’s method is used to discretize the Equation 4.55 to calculate the pressure drop across the loaded filter medium along the depth of the medium. Numerical solutions for partial differential equations are obtained by discretizing the partial differential equations. The thickness of the filter medium is discretized into n slices as shown in Figure 4.2 to find numerical solutions of equation 4.55, 4.26 and 4.11 to determine the filter performance along the depth of the medium. McCormick scheme is employed to solve Equation 4.26.

Figure 4.2 Filter medium is discretized into n slices to determine filter performance along the depth of the medium
4.3 Model results

4.3.1 Finding the appropriate DZ step

Figure 4.3 shows the particle size distribution of solid particles generated from the automated filter tester (TSI 8130) available in our lab. Most of the particles of significant size are in the range of 25 to 100 nm with a mean of about 75 nm. In our model, we considered only one particle size and assume the size to be 75 nm.

![Figure 4.3 Particle size distributions from Automated Filter Tester (TSI 8130) as measured by TSI 3080 SMPS.](image)

Table 4.1 lists the model conditions for our model. The filter is divided into number of slices and DZ is varied based on number of slices.

<table>
<thead>
<tr>
<th>dp (nm)</th>
<th>Number per cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>100</td>
<td>1.0E+07</td>
</tr>
<tr>
<td>200</td>
<td>8.0E+06</td>
</tr>
<tr>
<td>300</td>
<td>4.0E+06</td>
</tr>
<tr>
<td>400</td>
<td>2.0E+07</td>
</tr>
</tbody>
</table>

The appropriate DZ value is selected to make sure the filter performance values are insensitive to DZ steps. Table 4.2 lists the filter performance value for different DZ
values. Since filter performance values are identical for DZ = 2.5E-4 and DZ = 2E-4. The DZ step of 2E-4 is chosen for our model.

Table 4.1 Model conditions for different DZ steps

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Air</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>1 atm</td>
</tr>
<tr>
<td>Temperature</td>
<td>294 K</td>
</tr>
<tr>
<td>Filter thickness</td>
<td>1E-2 m</td>
</tr>
<tr>
<td>Porosity of the medium</td>
<td>0.98</td>
</tr>
<tr>
<td>Fiber diameter</td>
<td>5 micron</td>
</tr>
<tr>
<td>Diameter of dendrites</td>
<td>75 nm</td>
</tr>
<tr>
<td>Concentration of particles</td>
<td>10 mg/cc</td>
</tr>
<tr>
<td>Diameter of particles</td>
<td>75 nm</td>
</tr>
<tr>
<td>Face velocity</td>
<td>0.1 m/s</td>
</tr>
<tr>
<td>DZ</td>
<td>varied</td>
</tr>
<tr>
<td>DT</td>
<td>0.001 sec</td>
</tr>
<tr>
<td>Loading time</td>
<td>1 minute</td>
</tr>
</tbody>
</table>

Table 4.2 Filter performance values for different DZ steps

<table>
<thead>
<tr>
<th>Number of slices</th>
<th>DZ (m)</th>
<th>Pressure value from last slice (atm)</th>
<th>Capture efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1E-3</td>
<td>0.9982</td>
<td>81.4980</td>
</tr>
<tr>
<td>20</td>
<td>5E-4</td>
<td>0.9981</td>
<td>81.4258</td>
</tr>
<tr>
<td>30</td>
<td>3.33E-4</td>
<td>0.9980</td>
<td>81.4138</td>
</tr>
<tr>
<td>40</td>
<td>2.5E-4</td>
<td>0.9980</td>
<td>81.4018</td>
</tr>
<tr>
<td>50</td>
<td>2E-4</td>
<td>0.9980</td>
<td>81.4018</td>
</tr>
</tbody>
</table>
4.3.2 Varying the concentration of particles

Table 4.3 shows the model conditions for varying concentration of solid particles. The concentrations of solid particles are varied from 10 to 20 mg/cubic meter. The pressure drop and capture efficiency trend of the filter medium for varying concentration of solid particles is predicted (see Figure 4.4 and Figure 4.5). Both pressure drop and capture efficiency of the filter medium increases with the loading time for concentration of particles. Figure 4.6 shows the volume fraction of particles captured along the depth of the medium for different loading times for an inlet concentration of 10 mg/cubic meter, fiber diameter of 5 micron, velocity of 0.1 m/s, porosity of medium to be 0.98, inlet pressure of 1 atm and temperature of 294 K. For longer loading times, more particles are captured in the depth of the medium and accumulated particles inside the filter medium contribute towards the pressure drop and capture efficiency of the filter medium. Our model results shows that most particles are collected near the inlet face of the medium similar to the earlier works of particle loading on microfibrous filter medium [88].
## Table 4.3 Model conditions for varying concentration of solid particles

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Air</td>
</tr>
<tr>
<td>Inlet pressure and temperature</td>
<td>1 atm and 294 K</td>
</tr>
<tr>
<td>Filter thickness</td>
<td>1E-2 m</td>
</tr>
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</tr>
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</tr>
<tr>
<td>Diameter of dendrites</td>
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</tr>
<tr>
<td>Concentration of particles</td>
<td>varies</td>
</tr>
<tr>
<td>Diameter of particles</td>
<td>75 nm</td>
</tr>
<tr>
<td>Face velocity</td>
<td>0.1 m/s</td>
</tr>
<tr>
<td>DZ</td>
<td>2E-4 m</td>
</tr>
<tr>
<td>DT</td>
<td>0.001 sec</td>
</tr>
<tr>
<td>Loading time</td>
<td>1 minute</td>
</tr>
</tbody>
</table>
Figure 4.4 Pressure values at filter exit with respect to loading time.

Figure 4.5 Capture efficiency of the filter medium with respect to loading time.
4.3.3 Varying gas face velocity

The gas velocity is directly proportional to the drag force acting on the fibers (Equation 4.52). With an increase in gas face velocity, the drag force acting on the fibers increases resulting in higher pressure drop (Figure 4.7). Figure 4.8 shows the capture efficiency profile for different gas velocity with the increase in loading time.

Figure 4.6 Volume fraction of particles along the depth of the medium for various loading time.
Figure 4.7 Pressure at filter exit for different gas face velocity

Figure 4.8 Capture efficiency profile for different gas face velocity
4.4 Conclusion

The model was developed to predict the filter performance taking into account of particle accumulation along the depth of the filter medium. The parametric study was done to predict how the filter performance varies for parameters such as gas face velocity, concentration of particles and loading time. The future work includes the comparison of model results with experimental one as discussed in Chapter 8.

NOTATION

$A =$ Area of filter media

$Cn =$ Cunningham factor

$D =$ Coefficient of diffusion

$d_i =$ diameter

$g =$ Acceleration due to gravity

$= $ particle diameter

$E_i =$ Single fiber efficiency

$E_R, E_D, E_{DR} =$ Single fiber efficiencies by direct interception, diffusion, and combined diffusion and interception mechanisms

$= $ Drag force of fiber in $Z$ direction

$F_{tot} =$ Total force acting on the filter

$f_i =$ Drag force per unit length of fiber of diameter $d_i$

$Kn =$ Knudsen number
= Boltzmann’s constant, \(1.38066 \times 10^{-23}\) J/°K

\(L\) = Filter thickness

\(L_i\) = Total length of fibers of diameter \(d_i\) within elemental volume of the filter medium

\(N_R\) = Ratio of diameters, \(d_p/d_i\)

\(P, \Delta P\) = Gas phase pressure, pressure drop across filter

\(P_e\) = Peclet number

\(QF\) = Quality Factor

\(RQF\) = Relative quality factor (QF of the medium/QF of medium of only microfibers)

\(v_z^G\) = intrinsic gas phase velocity in the \(z\) direction

\(G\) = Transport of property \(\varphi\) across an interphase boundary due to heterogeneous reaction

\(S\) = Transport of property \(\varphi\) across an interphase boundary due to interfacial curvature

\(E\) = Convective transport of property \(\varphi\) across an interphase boundary

\(I\) = Mechanical flux of property \(\varphi\) across an interphase boundary

\(w_0^G\) = Mass fraction of aerosol particles in the gas phase

\(w_{in}, w_{out}\) = Inlet and outlet mass fractions of particles in gas phase

\(\alpha\) = Overall Filter Coefficient for the filter medium

\(\alpha_i\) = Filter Coefficient of a 100% efficient fiber

= porosity of the media
= Solidity of the media

ζ' = Hydrodynamic factor

λ = mean free path of air molecules (0.065 μm at 25°C and 1 ATM pressure)

η = particle mobility

μ = viscosity of gas phase

ρ = density

t = time

m = mass concentration of aerosol particles in the gas phase, kg/m³

v = Velocity of the fiber in Z direction

T = Temperature

Superscripts

G = Gas phase

S = Solid (fiber) phase

Subscripts

i = fiber

p = particle

Z = Z-direction

o = region property (property summed over all phases)

A = Species A
CHAPTER V
Model Comparison of Filter Media for Hot Gas Filtration

5.1 Introduction

High temperature gases occur in industries such as power production, petrochemicals, and metallurgy. In power production, temperatures of dust laden hot gases are well above 1000°C. Economically, it would be advantageous to use the high energy potential of hot exhaust gases for producing electricity [109]. However, common polymer or cellulose based dust filters are limited in their operating temperatures due to the low melting temperatures of the materials, erosion by dust particles at the elevated temperatures, and the corrosive effect of aggressive liquid vapors. Particulates in the gases can be harmful to turbines, downstream processes or the environment. Removal of the particulates from the hot gases requires filter media that can endure the high temperatures. More durable high temperature materials include porous metals, glass or ceramics. Of these, ceramics may be the most promising for the development of high temperature fabrics for filters. Ceramic filters can be either fibrous, granular or monolith form. Filtration experiments of hot gases are difficult and expensive. Before such experiments are undertaken, mathematical models should be evaluated to determine what designs are most effective. Our model compares the performance of three filter designs for their performance at capture of submicron sized particles.
5.2 Objective

The Objective of this modeling to find out the quality factor and pressure drop across the media for three different types of filters at same specific conditions. The quality factor is defined as $-\ln (\text{Cout}/\text{Cin})$/Pressure drop. Pressure drop is related to energy expenditure in filtration. Thus, quality factor is a measure of the performance of the filter achieved against the energy expended. The higher the quality factor, the lower the energy expended to achieve the same separation.

5.3 Model Development

In this model initially the gas phase is modeled at 21°C to make sure the model provides calculation results comparable to laboratory observations. The best media design determined from the comparison at 21°C (the fibrous media) is further modeled for gases at high temperatures in Section 5.4. For this initial case, air at 20 psi and 21 degree Celsius passes through three different types of filters at similar conditions. Particles in the range of 100 nm to 300 nm are the considered to be most penetrating sizes and industries are interested in improving capture efficiency of particles in this range. Thus, filtration of 150 nm spherical particles is considered for our modeling study.

Some of the common assumptions which are taken into account for three filters are:

1. Steady state
2. Isothermal process
3. One dimensional flow, only in Z – direction, at the volume averaged scale
4. Flow is evenly distributed among the fibers or granules or pore
5. The permeability’s of the media are uniform and isotropic
6. Incompressible filter media
7. Effects of binder materials are neglected
8. The model only considers clean filter media. Performance does not consider particle loading of the filter media
9. Particle loading is not considered
10. All fibers, pores, grains are uniform in size
11. All of the filters were modeled having the same inlet surface area (hence same inlet mass flux)
12. The filters are sized and compared for capture efficiency of 99%.

   The operating conditions are assumed the same for each of the filters in which the mass flow rate of air through the filter is steady at 7.25 g/s. This flow rate corresponds to a typical cartridge depth filter operating at 138 KPa (20 psi) at 21° C. The approach velocity of the gas is calculated from the mass flux and the density, hence varies with pressure and temperature. All of the filters are assumed to have six centimeter diameter inlet areas for this study.

5.3.1 Fibrous filter

   Fibrous filter media are formed by packing fibers loosely and particle retention takes place mostly within the interior of the media (see Figure 5.1). Fibrous filters have the advantage of high capture efficiency and low pressure drop because of small fiber diameter and high porosity [114]. The model considers single fiber mechanical capture mechanisms. Monodispersed spherical particles of 150 nm are assumed to challenge the filters. The porosity of the filters prepared in our laboratory have porosities in the range
of 0.95 – 0.98. For this modeling, we consider porosity to be 0.95. Direct interception and Brownian diffusion are the dominant mechanisms of this particle size and hence other capture mechanisms like inertial impaction and gravitational settling are ignored.

A volume averaged continuum theory is used to model the process. The gas stream with solid particles flows through the fibrous media and the particles are captured in the depth of the filter. The set of working equations derived here for this particular model represent balances on mass continuity, momentum and species balance for each phase. The mass and species balance are used to determine the aerosol outlet concentration. The gas phase momentum balance is used to determine the pressure drop across the filter medium.

The above assumptions are applied to the conservation equations to simplify the equations.

The gas phase momentum balance gives
Integrating the above equation from 0 to L

The pressure drop across the media is related to the total force acting on all fibers by

Total force acting on all fibers is related to force per unit length of fibers by

Where $L$ is the total length of fibers of diameter $d$.

Substituting Equation 5.5 in Equation 5.3 gives

Length of fibers is related to the volume fraction of fibers by

Substituting $\phi$ in Equation 5.6 yields

Substituting Equation 5.8 in 5.2 gives

Expression for $f$ for slip flow regime is given by

Substituting Equation 5.10 in 5.9 gives
The equation 5.11 is used to determine the pressure drop across the fibrous filter. The gas phase mass balance and gas particle species balance are used to determine the aerosol outlet concentration. At start up condition, the gas phase mass balance reduces to

\[ \text{---} \]

The gas phase particle species balance gives

\[ \text{---} \]

where \( I_0^C \) = mass flux of aerosol particles captured from gas phase onto the fibers. The mass fraction aerosol particles in the gas phase \( w_0^G \) is the ratio of mass concentration of particles to the mass density of the gas

\[ \text{---} \]

The species balance is solved by finding a constitutive equation for the mass transfer term. It is given by

\[ \text{---} \]

Substituting Equation 5.16 in 5.14 gives

\[ \text{---} \]

From Equation 5.13 the constant product can be taken out of the derivative, therefore,

\[ \text{---} \]
On integrating Equation 5.19 from 0 to L

The overall filter coefficient, \( \alpha \) is related to the single fiber efficiency by

where \( E_i \) is the capture efficiency and \( \varepsilon_i \) is the volume fraction of the filter media occupied by fibers of diameter \( d_i \).

Correlations for the single fiber capture efficiencies (\( E_i \)) are available from single fiber theory [75]. The dominant mechanisms for submicron particle size are direct interception and Brownian diffusion. Other capture mechanisms are considered negligible in this model. Single fiber capture efficiency by diffusion and direct interception accounting for aerodynamic slip is calculated from

Brownian diffusion efficiency (\( E_D \)) is calculated from

Direct interception efficiency (\( E_R \)) is calculated from

The combination term of interception and diffusion is calculated from
Where $\frac{d}{D}$ is the ratio of the diameters of the particles to the fibers,

$$5.27$$

Knudsen number $\frac{\lambda}{D}$ is the ratio of the mean free path of air molecules to fiber diameter,

$$5.28$$

The Peclet number is

$$5.29$$

where the diffusion coefficient of the particles is given by

$$5.30$$

and $\mu$ is the mobility given by

$$5.31$$

$$5.32$$

$$5.33$$

The constants are $A = 1.246$, $Q = 0.42$ and $B = 0.87$.

The mean free path of air molecules at $25^\circ$C and 1 ATM pressure is $\lambda = 0.065 \mu$m. The filter coefficient $\alpha$ is calculated using the above equations and hence, the outlet concentration of particles are calculated using Equation 5.20.

For the fibrous filter, Equation 5.20 provides concentration profile

$$\frac{C_{out}}{C_{in}} = \exp(-\alpha L)$$

Equation 5.11 provides the pressure drop across the fibrous filter
The quality factor for fibrous filter is

\[ QF = \left( \frac{\alpha L}{\Delta P} \right) \]

5.3.2 Granular filter

For a granular filter the gas stream flows through the filter composed of granules or grains (see Figure 5.2) and the particles are deposited onto the grains. Many granular substances are temperature and corrosion resistant and thus, granular filters are suitable for treating high temperature and corrosive gaseous streams.

Figure 5.2 Schematic diagram of granular filter medium

Particle deposition on the grains is similar to the capture mechanisms involved with fibrous filter media. The porosity of the granular filter is considered as 0.3. Happel’s model is used for modeling of granular filters because of its accuracy compared to other models. In Happel’s model, a granular filter is a collection of identical cells.
consisting of a solid sphere of radius $a_c$ surrounded by a gas envelope of radius $b$. The correlation between $a_c$ and $b$ is defined as [114]

$$\frac{a_c}{b} = (1 - \varepsilon)^{\frac{1}{3}}$$

5.35

The correlation for the particle capture by direct interception for Happel’s model is given as [114],

$$E_R = 1.5 A_s (1 - \varepsilon)^{\frac{2}{3}} N_R^2$$

5.36

Where $A_s$ is defined as [114],

$$A_s = 2 \left(\frac{1-p}{w}\right)^5$$

5.37

$$w = 2 - 3p + 3p^5 - 2p^6$$

5.38

$$p = \frac{a_c}{b} = (1 - \varepsilon)^{\frac{1}{3}}$$

5.39

The aspect ratio is

$$N_R = \frac{d_p}{d_g}$$

5.40

$d_g$ - Grain or collector diameter.

Particle capture by Brownian diffusion for granular filter is given as [114]

$$E_D = 4(1 - \varepsilon)^{2/3} A_s^{1/3} N_{pe}^{-2/3}$$

5.41

$Pe$ - Peclet number $= \frac{V_Z^G d_g}{D}$

5.42

Overall capture efficiency of a filter is given as

$$(1 - E_{RD}) = (1 - E_R)(1 - E_D)$$

5.43
The concentration profile for a granular filter medium is given by [114]

\[
\left( \frac{C_{\text{out}}}{C_{\text{in}}} \right) = \exp \left( -1.5 \frac{E_{\text{RD}}}{d_g} L (1 - \varepsilon) \right)
\]

5.44

The pressure drop across a granular filter medium is given by [115]

\[
\left( \frac{\Delta P}{\Delta L} \right) = \left( 180 \left( \frac{1 - \varepsilon}{N_{\text{Re}}} \right) + 1.8 \left( \frac{1 - \varepsilon}{\varepsilon^3} \right) \rho V_z G^2 \right) \frac{d_g}{d_g}
\]

5.45

Reynolds number \( N_{\text{Re}} = \frac{\rho d_g V_z}{\mu} \)

5.46

The quality factor for granular filter medium is given as

\[
QF = \frac{1.5 E_{\text{RD}} \varepsilon^3}{180 \left( \frac{1 - \varepsilon}{N_{\text{Re}}} \right) + 1.8 \rho V_z G^2}
\]

5.47

5.3.3 Monolith filter

A monolith filter is a single cylindrical block containing many pores in the shape of circular tubes aligned in the direction of the length (see Figure 5.3). The pores that are alternatively plugged as that of a honeycomb structure are not considered for this model. It is assumed that gas flows through filters and all particles that touch the pore wall are captured.
For monolith filters, Brownian diffusion is the dominant mechanism, since the particles diffuse through the fluid and get captured on the walls of the pores. Re-entrainment is not considered in this model. The equation of continuity for the species balance is solved to determine the concentration profile for flow in a pore of the monolith filter.

The species balance is given as

\[ \nu_z \frac{\partial C_A}{\partial z} = -\frac{\partial J_{Ar}}{\partial r} \]  \hspace{1cm} 5.48

Where \( J_{Ar} \) is the molar diffusion flux. The molar diffusion flux at the pore wall is

\[ J_{Ar} \bigg|_{D_{pore}/2} = -\frac{k_x}{c} (C_A - C_w) \]  \hspace{1cm} 5.49

where

\( C_A = \) Molar concentration of the species.
\( C_w = \) Concentration at the surface of the wall = 0
\( k_x = \) Mass transfer coefficient determined from correlations
\[ c = \text{Molar concentration of the mixture.} \]

The species balance Equation 5.48 can be written as

\[
D_{\text{pore}} V_z \frac{\partial C_A}{\partial z} = -\frac{k_c}{c} (C_A - C_w) \tag{5.50}
\]

\(\frac{k_c}{c}\) is calculated from the following correlations (Equations 3.52-3.55). For Laminar flow regimes \([116-117]\)

At low \(Gz\), \(Sh = 3.66\) \(\tag{5.51}\)

\(Gz > 20, Sh = 2.0Gz^{1/3}\) \(\tag{5.52}\)

Where Grätz number, \(Gz = \frac{\pi D_{\text{pore}} Pe}{4L}\) \(\tag{5.53}\)

Sherwood number, \(Sh = \frac{k_c D_{\text{pore}}}{cD}\) \(\tag{5.54}\)

Boundary conditions for the monolith filter are (Figure 5.4),

\(z = 0, C_A = C_0\) \(\tag{5.55}\)

\(z = L, C_A = C_L\) \(\tag{5.56}\)

\(z = 0, C_A = C_0\)

\(r = D_{\text{pore}} / 2, C_A = C_w\)

\(z = L, C_A = C_L\)

Figure 5.4 Schematic diagram showing the boundary conditions for a pore in a monolith filter.

Applying the boundary conditions Equation 5.55 and Equation 5.56 in Equation 5.50 yields
\[
(C_L - C_w) = (C_0 - C_w) \exp \left( -\frac{k_x L}{cD_{pore} V_z} \right) \quad 5.57
\]

\(C_o\) - Concentration at the entrance of the filter

\(C_L\) - Concentration at the exit of the filter medium

Simplifying the Equation 5.57 yields the concentration profile along the length of the monolith filter,

\[
\frac{C_L}{C_O} = \exp \left( -\frac{k_x L}{cD_{pore} V_z} \right) \quad 5.58
\]

The average velocity \(V_Z\) is defined as

\[
V_Z = \frac{\text{Volumetric flow rate through filter}}{\text{Total number of pores} \times \text{cross sectional area of pore}} = \frac{Q}{N_{pore} \left( \pi D_{pore}^2 / 4 \right)} \quad 5.59
\]

where \(Q\) is volumetric flow rate passing through the monolith filter medium and is calculated by

\[
N_{pore} = \frac{\text{Area of filter}}{\text{Area of pore}} \quad 5.60
\]

The area of the pore is calculated by considering it as a square for approximation and is defined as

\[
\text{Area of the pore} = D_{pore}^2 \quad 5.61
\]

Thus, the total number of pores is calculated by

\[
N_{pore} = \frac{\pi}{4} \left( \frac{D_{\text{filter}}}{D_{pore}} \right)^2 \quad 5.62
\]
Pressure drop for a circular tube is calculated by the Bernoulli’s Equation \([117]\) and by Churchill’s Equation for the friction factor \([118]\):

\[
\Delta P = \left( \frac{4 \rho L V^2}{D_{\text{pore}}} \right)^2 \left[ \frac{8}{N_{\text{Re}}} \right]^{12} + \left[ 2.457 \ln \left( \frac{N_{\text{Re}}}{7} \right) \right]^{16} + \left[ \frac{37530}{N_{\text{Re}}} \right]^{16} \right]^{-1.5} - 1/12
\]

Substituting the pressure drop and concentration profile in quality factor definition yields,

\[
QF = \left( \frac{\rho V_x c}{k_c} \right) \left[ \frac{8}{N_{\text{Re}}} \right]^{12} + \left[ 2.457 \ln \left( \frac{N_{\text{Re}}}{7} \right) \right]^{16} + \left[ \frac{37530}{N_{\text{Re}}} \right]^{16} \right]^{-1.5} - 1/12
\]

5.3.4 Model Results

Figure 5.5 – 5.7 show the comparison between the lengths, pressure drops and quality factors of fibrous, monolith and granular filters as a function of the characteristic medium dimension: diameters of the fibers, pores and grains. These filters are challenged with the same particle size at the same mass flow rate, and having the same 99% capture efficiency.

Figure 5.5 shows that the length of the granular filter is less for all diameter grains compared with fibrous and monolithic filter. Fibrous and monolithic filters are very lengthy in order to attain same capture efficiency having the same characteristic dimension. Another way to look at this data is suppose you want the filter to be 1 cm thick, then the monolith must have 1 micron pores, the fiber media must have 4 micron fibers, and the granular filter must have 20 micron particles.

One factor that contributes to the difference in length is the volume fraction of the filters. The length of filters for monolith and fibrous filter for diameter greater than 100
μm in order to achieve targeted capture efficiency is of unrealistic value for practical applications.

![Graph showing Length of fibrous, monolithic, and granular filters for varying diameters to attain targeted 99% capture efficiency.](image)

Figure 5.5 Logarithmic plot of Length of fibrous, monolithic and granular filters for varying diameters to attain the targeted 99% capture efficiency.

From Figure 5.6, it is evident that the pressure drop across the fibrous filter is least for all diameters compared with granular and monolith filter medium. From Figure 5.7, the quality factor for the fibrous filter is higher than the other two filters, because of the lower pressure drop in fibrous filter.
Figure 5.6 Logarithmic Plot of Pressure drops of fibrous, monolithic and granular filters for varying diameters at same filter diameter, particle size, flow rate and capture efficiency.

The quality factor of the fibrous filters decrease and then increases as fiber diameter is increased. The quality factor at 1 μm is about the same values as the quality factor at 100 μm. Thus, the choice is between finer fiber diameters with thicker fiber diameter. Larger fiber diameter requires thicker filter media to achieve the specified capture efficiency. Fabrication of filter medium with finer fiber diameter looks promising. We can conclude that fibrous filter media seems to be the best option for making the high temperature filter medium due to lower pressure drop, higher quality factor and the thickness of filter media is of realistic value, when fiber diameter is less than 100 μm. Our next step is to model the fibrous filter media for higher temperatures.
5.4 Comparison of modeling and experimental results

Filter media of 5.9 cm diameter and 1 cm thickness with a porosity of 0.98 was fabricated using the vacuum molding process. The filter media was made using a 5 micron glass fibers. The experiments were carried out using Automated filter tester (TSI 8130). The experimental conditions were 1 atm, 294 K, face velocity of 0.15 m/s. The capture efficiency was 90%. For similar conditions, model predicted the thickness of the media to be 1.1 cm. Thus, comparison shows that model prediction are closer to the experimental one. The model is further extended for high temperature gases.
5.5 Analytical Model of Fibrous Filter at High Temperatures

Modeling of fibrous filter media is done at the same conditions which were stated above except for in the gas temperature. Temperature dependence on fluid properties such as gas viscosity and density are taken into account in this model. From Figure 5.8 the length of a fibrous filter decreases with increase in temperature for fiber diameters less than 15 microns and the length increases for fiber diameters greater than 15 microns. The 15 micron fiber diameter is near the diameter at which slip flow becomes important to the pressure drop and this reversal of the trend is due to the slip flow effects on capture efficiency. Figure 5.9 shows the pressure drop increases with the rise in temperature which corresponds to the increase in gas velocity to maintain the same mass flow rate of gas at increasing temperatures. The quality factor of the media decreases as temperature increases. This is because direct interception dominants the capture mechanism at lower temperatures and Brownian diffusion is dominant mechanism at higher temperatures.
Figure 5.8 Logarithmic plot of length of fibrous filters for varying fiber diameters at three different temperatures.

Figure 5.9 Logarithmic plot of pressure drop of fibrous filters for varying fiber diameters at three different temperatures.
Figure 5.10 Logarithmic plot of Quality factors of fibrous filters for varying diameters at three different temperatures.

5.5 Conclusions

The model results show us how the pressure drop across the media, quality factor and media length vary with changing media grain, fiber, or pore diameters and how they change with operating temperature. The fibrous filter medium is the best filter structure because of its lower pressure drop.
CHAPTER VI

ELECTROSPINNING OF POLYMERIC AND CERAMIC NANOFIBERS

6.1 Objectives

The objectives of this study are to fabricate polymeric and high temperature resistant ceramic nanofibers for filtration applications. Mass production of nanofibers is of utmost significance for filtration applications and hence, nanofibers are synthesized from various electrospinning setups as described in this chapter.

6.2 Introduction

Electrospinning is a process by which a polymer solution can be spun into small diameter fibers less than 500 nm using a high potential electric field. The apparatus used for electrospinning is simple in construction. It consists of a high voltage source, a syringe, a syringe pump and a grounded collector. The grounded collector can be of any shape such as flat plate or rotating drum. A schematic of the electrospinning process is shown in Figure 6.1. The symbol + in Figure 6.1 represent same charge carried by the jet. The polymer solution that is to be spun is forced through a syringe pump or allowed to flow from a capillary tube or pipette to form a pendant drop of the polymer at the tip of the capillary. High voltage potential is applied to the polymer solution and the collector is grounded. The electric field causes a droplet of a polymer to form a cone shape.
At the apex of the cone, the flow field is unstable and the material launches a jet. As the jet moves away from the drop, charge imbalances cause the jet to bend and stretch. The stretching causes the jet diameter to decrease and the solvent in the polymer jet solution evaporates, causing the jet to stiffen into the form of a fiber so that the diameter is in the nanometer scale range. The formation process is relatively fast and continuous.
fibers are produced. Scale-up also appears to be possible. The electrospinning technique is a reasonable approach to produce continuous nanofibers.

6.3 Electrospinning setups for mass production of nanofibers

6.3.1 Single or double jet Electrospinning setup

The electrospinning apparatus in Figure 6.2 consists of high voltage supply, grounded collector and a syringe pump. The collector is in the form of rotating cylindrical drum and an aluminum foil is wrapped over the outer surface of the cylindrical drum as the collecting surface. A motor is used to rotate the cylindrical drum. The syringe pump (World Precision Instruments, SP101i) is used to pump a constant flow rate of polymer solution during the electrospinning process. One or two syringes are mounted on the syringe pump and solution is pumped to the needles through a teflon tube (Newage Industries). The rotating drum and needles are not aligned vertically but are placed in such a way that the occasional drips of polymer solution from the needle do not fall onto the collector. A high voltage supply (Gamma High Voltage, ES 30P-5W) is applied to overcome the surface tension of the solution and launch the jets. Polymer jets undergo a bending instability and long, continuous nanofibers are collected on the drum. The mass of nanofibers collected from single jet is around 0.05 g/hour.
6.3.2 Multi-jet Electrospinning setup

A multi-jet electrospinning setup was developed in our lab to increase the mass production of nanofibers [119]. The polymer solution is loaded into polymer reservoir and delivered to a porous cylindrical tube by applying air pressure to the reservoir. Droplets are formed from the partially drilled holes. The high voltage electrode is positioned inside of the cylindrical tube. As the voltage is applied, jets are launched from
the 10 holes spaced 1 cm apart from each other and nanofibers are collected onto the rotating drum. The mass production rate of nanofibers is around 0.3 – 0.5 g/hour.

6.3.3 Nanospider setup

Jirsak et. al designed a Nanospider machine which uses a semi-submerged smooth rotating cylinder as the electrode to pick up drops of solution from polymer bath and nanofibers are spun towards the collector (Figure 6.4) [66]. Figure 6.5 (a) shows the
close-up view of the collector and rotating electrode in the Nanospider setup. The polymer solution is loaded in the polymer bath, which has the rotating electrode. Elmarco offers different structural types of electrode. Figure 6.5(b) shows a smooth rotating electrode and (c) is the wire electrode. The mass production rate of nanofibers is around 2.5 -3 g/hour.

Figure 6.4 Elmarco Nanospider machine
Figure 6.5 (a) Closer view of Nanospider machine (b) Polymer bath with smooth rotating electrode (c) Wire electrode.

6.4 Fabrication of polymeric nanofibers

Polymeric nanofibers are used in a number of commercial air filtration applications and have lot of potential for other filtration applications too [91]. The
electrospun polymeric nanofibers are used for the fabrication of nanofiber filter medium in our lab. Most commonly electrospun polymeric nanofibers are Polyvinylpyrrolidone (PVP) nanofibers and Nylon 6 nanofibers. The Nylon 6 nanofibers are used for the fabrication of nanofiber filter media because Nylon 6 nanofibers do not dissolve in water during the slurry preparation.

6.4.1 Fabrication of Nylon 6 nanofibers

Figure 6.6 shows the procedure used for the fabrication of Nylon 6 nanofibers. 10 weight percent of Nylon 6 is dissolved in formic acid and kept in the shaker for mixing the solution. The shaker is kept at the temperature of 40°C during the mixing hours (Figure 6.7). The polymer solution is usually mixed for 4 to 6 hours. The solution is directly electrospun into nanofibers and are characterized using Scanning Electron Microscopy (SEM) (Figure 6.8). The average fiber diameter of Nylon 6 nanofibers is 196.2 ± 16.5 nm.
Figure 6.6 Recipe for fabricating Nylon 6 nanofibers

1. 10 weight percent of Nylon 6 dissolved in formic acid
2. Heating the above polymeric solution at 40°C for 6 hours
3. Electrospinning the above solution
4. Characterization of nanofibers

Figure 6.7 Shaker for mixing solution
6.4.2 Characterization of nanofibers

A small piece of nanofibers mats is cut and placed on the carbon tape attached to the stub. The nanofiber sample is coated with silver using a sputter coater (EMITECH K575X) (Figure 6.9). The coating is done for 25 seconds at a current of 55 mA. The prepared sample is viewed under Scanning Electron Microscope (FEI QUANTA 200 Enviornmental Scanning Electron Microscope) (Figure 6.10).
Figure 6.9 Sputter Coater

Figure 6.10 Environmental Scanning Electron Microscope (ESEM) with Energy dispersive X-ray Spectroscopy (EDS)
6.4.3 Synthesis of ceramic nanofibers

Ceramic nanofibers that are fabricated in our lab are high temperature resistant nanofibers and can withstand temperature in the range of 1000°C. The ceramic nanofibers are flexible and are continuous long nanofibers. The basic steps involved in synthesizing ceramic nanofibers are as shown in Figure 6.11

1. Preparation of ceramic precursor solution
2. Preparation of polymeric solution
3. Mixing ceramic precursor solution and polymeric solution in appropriate weight ratio
4. The above solution is electrospun into nanofiber mats
5. Calcined at 600°C for 4 hours to remove polymers from the nanofibers mats and thus, ceramic nanofibers are synthesized

Figure 6.11 Basic steps involved in synthesizing ceramic nanofibers

Polymer solution is mixed with ceramic precursor solution because it is difficult to electrospin ceramic precursor solution directly. Addition of polymer solution to the ceramic precursor solution provides the appropriate viscosity to electrospin the composite solution into nanofiber mats.

6.4.4 Fabrication of alumina nanofibers
Steps involved in fabricating alumina nanofibers are described in steps (Figure 6.12). Polymer solution is prepared by dissolving 9 weight percent of PVP in ethanol. The ceramic precursor solution is prepared by mixing aluminium acetate solution, formic acid and water in the weight ratio of 1:1:2.5. Polymer and ceramic precursor solution are separately mixed in the shaker for 10 hours at 40°C. The well-mixed polymer and ceramic precursor solution are mixed in the weight ratio of 1:1. The above prepared solution is electrospun into nanofibers mats. The nanofibers mat is calcined at 600°C for 4 hours to remove polymers and thus, alumina nanofibers are synthesized (Figure 6.13). The average fiber diameter of alumina nanofibers electrospun from Nanospider machine is $369 \pm 78$ nm.
Thermal gravimetric analysis (TGA) is done to ensure that the polymers are degraded when calcined at 600°C. TGA experiment is performed by heating a sample of a electrospun alumina and PVP nanofbers mats to 800°C in air.
Figure 6.13 SEM image of Alumina nanofibers.

Figure 6.14 Thermal Gravimetric Analysis of PVP/aluminium acetate nanofibers mat.
The TGA result shows the reduction in weight of the sample with the increase in temperature and weight of the sample is stable from 550°C to 800°C (Figure 6.14). This result indicates that all polymers are degraded at 550°C and the remaining samples are only alumina nanofibers. Energy Dispersive X-ray Spectroscopy (EDS) is used for the elemental analysis of the sample. The EDS results shows the presence of carbon for a PVP-alumina nanofibers before the calcination step (Table 6.1 and Figure 6.15) and EDS shows the absence of a carbon peak from the same sample after it is calcined at 600°C for 4 hours (Figure 6.16 and Table 6.2). This results confirms that polymers are completely degraded from the nanofibers mats after the calcination step and resulting in inorganic alumina nanofibers.

Table 6.1 Elemental analysis of PVP/Aluminium acetate nanofibers mat

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight percentage (%)</th>
</tr>
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<tbody>
<tr>
<td>C</td>
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</tr>
<tr>
<td>Al</td>
<td>3.37</td>
</tr>
<tr>
<td>O</td>
<td>31.99</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
</tr>
</tbody>
</table>
Figure 6.15 EDS spectrum of PVP/aluminium acetate nanofiber mat

Table 6.2 Elemental analysis of Alumina nanofibers

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>O</td>
<td>59.25</td>
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<tr>
<td>Total</td>
<td>100.00</td>
</tr>
</tbody>
</table>
6.5 Conclusion

The polymeric and ceramic nanofibers are successfully electrospun from the setup. The ceramic nanofibers can withstand a very high temperature of 1000°C. The electrospun nanofibers will be used for the preparation of nanofiber filter medium as described in Chapter VII.
CHAPTER VII
DEVELOPMENT OF NANOFIBER ENHANCED FILTER MEDIUM

7.1 Objectives

In this chapter the method for fabricating filter medium with nanofibers is described. Two different types of filter media are developed for different filtration applications. Filter media with polymeric nanofibers are developed for air filtration applications. The second type of filter medium is developed with ceramic microfibers and ceramic nanofibers for hot gas filtration to sustain high temperature in the range of 1000°C. Filter media enhanced with nanofibers primarily consist of microfibers, nanofibers and binders to hold fibers together. Different binders were investigated for ceramic filter medium using a flow rate failure test setup. This setup was constructed in our lab.

7.2 Procedure for making filter media using a vacuum molding method

The filter medium is prepared by vacuum molding an aqueous slurry of fibers. Vacuum molding method consist of two steps namely slurry preparation and vacuum molding process to make filter medium.

7.2.1 Slurry preparation

The slurry is prepared by mixing microfibers, starch and binder in 8 liters of water. The dilute sulphuric acid prepared in our lab is added to 8 liters of water and the pH is in the range of 2.75. This pH range offers optimum binding capability for binders [120]. The 3 grams of microfibers based on final thickness of filter medium is initially
blended using blender. The blended microfibers are added to the 8 liters of water. The 0.2 g of corn starch, which is cationic is added to the slurry (fibers are usually negatively charged) to enhance the uniform dispersion of fibers in the slurry [121]. The 4 ml of binders are added to the slurry. The binders hold the fibers together and provide structural support to the filter medium. The stirrers are used to mix the slurry for approximately 30 – 45 minutes for uniform dispersion of materials (Figure 7.1). The initial blending of fibers using blender has significantly improved the drainage of water during the vacuum molding process. The slurry made with fibers without blending step often took more time during the vacuum molding process. When nanofibers are added to fabricate nanofiber filter medium, electrospun nanofibers are added along with the blended microfibers in 8 liters of water and follows the similar slurry preparation procedure to that of microfiber filter medium. While preparing nanofiber filter medium with different amount of nanofibers added to the medium, microfibers along with nanofibers are blended using blender and are added to the 8 liters of water. Then, the slurry is once again blended 2 to 3 times and this step helps in reducing the vacuum molding process time. Stirrer which is used in final step of slurry preparation in microfiber filter medium for better dispersion of fibers are often skipped for nanofiber filter medium preparation because high speed rotation of stirrer often causes the nanofibers to get stuck with stirrer parts. Care should be taken during stirrer step so that nanofibers disperse uniformly while using stirrer.
Figure 7.1 Stirrer for slurry preparation.

7.2.2 Vacuum molding process

The vacuum molding setup consists of a mixing tank, drain tank and vacuum pump (Figure 7.2 (a)). The mixing tank has a plexiglass hollow mold with a steel mesh having diameter of 6 cm which is the diameter of the filter medium in this case (Figure 7.2 (c)). The Whatman 113 filter paper is placed over the steel mesh and removable plexiglass mold parts are assembled with the mixing tank (Figure 7.2 (b)). The above prepared slurry is poured into the mixing tank and is agitated using air bubbles during vacuum molding process. The air bubbles are generated by passing air through tubes. A vacuum of about 30 to 35 kPa is applied using vacuum pump to pull the slurry through the mold and to form the filter cake on a wire mesh metal screen and liquid is temporarily stored in drain tank. The wet molded filter medium is removed from the vacuum mold and heated to 120°C for 2 hours to remove water from the filter medium and thus, microfiber or nanofiber enhanced filter medium are fabricated. In the case of ceramic nanofiber filter medium, filter medium are heated in the furnace for 700°C for 10 hours in
order to let binders set the filter medium. The figure shows the 6 cm filter medium after vacuum molding process (Figure 7.3).

Figure 7.2 (a) Vacuum molding setup (b) Filter mold assembled with filter paper on the top of a 6 cm steel mesh (c) Filter mold with steel mesh in the center.
7.3 Selection of materials for nanofiber filter medium for air filtration applications

7.3.1 Microfibers:

Glass microfibers are used for making filter medium to test them for air filtration experiments using Automated Filter Tester (TSI 8130). The average fiber diameter is $4.95 \pm 1.39$ micron.

7.3.2 Nanofibers

Nylon nanofibers are used for making nanofiber filter medium for air filtration applications. Electrospun nylon nanofibers are chopped and added to the slurry preparation. Amount of electrospun nanofibers added to the slurry varies based on the
surface area ratio of nanofibers to microfibers. For area ratio of 1, 0.09 g of nanofibers is added to 3 g of microfibers during the slurry preparation. Thus, nanofiber enhanced filter medium are fabricated for different area ratios in the range of 0 to 2. The average fiber diameter is $202.7 \pm 41$ nm. Figure 7.5 shows the SEM image of nylon nanofibers.

![SEM image of nylon nanofibers](image)

Figure 7.5 SEM image of nylon nanofibers (same as Figure 6.8).

7.3.3 Binders

Megasol S50 from Wesbond Corporation is used as a binder to provide the structural strength to the filter medium.

7.4 Selection of materials for ceramic nanofiber filter medium for high temperature applications

7.4.1 Microfibers

Alumina microfibers are commercially manufactured by Thermal Ceramics under the name Saffil (Bulk HA). Alumina microfibers are brought from Thermal Ceramics. It can withstand temperature upto 1600°C. The average fiber diameter of alumina microfibers are $2.8 \pm 0.5$ micron (Figure 7.6).
7.4.2 Nanofibers

Alumina nanofibers which withstand temperature in the range of 1000°C are electrospun in our lab. The average fiber diameter of alumina nanofibers using Nanospider machine is $369.4 \pm 78$ nm.

Figure 7.6 SEM image of alumina microfibers.

Figure 7.7 SEM image of Alumina nanofibers (same as Figure 6.13).

7.5 Evaluation of different binders
Our main objective is to find appropriate binder which can withstand very high temperature in the range of 1000°C and hold fibers together for the ceramic filter medium. Some of the binders which are considered for ceramic filter medium are listed below:

7.5.1 B-glass microfibers (Hollingsworth and Vose).

B-glass fibers melt around 600°C completely and used as a thermal binder to provide structural strength to the filter medium [122]. The filter medium with B glass fibers were heated at 700°C for 10 hours to melt the B glass fibers. Figure 7.8 shows the SEM image of alumina microfiber with melted B glass fibers.

![SEM image of alumina fibers with melted B glass fibers](image)

Figure 7.8 SEM image of alumina fibers with B glass fiber as thermal binder.

7.5.2 Alumina Rigidizer (Zircar Ceramics)

Alumina rigidizer is water based colloidal suspension of alumina hydrate [123]. It can withstand temperature upto 1650°C. Alumina rigidizer hardens the ceramic fibers, when heated to a temperature of 600°C. Ceramic filter medium with alumina rigidizer as a binder were heated at 700°C for 90 hours. Figure 7.9 shows the SEM image of alumina fibers with alumina rigidizer.
7.5.3 Megasol S50 – silica binder (Wesbond Corporation)

The binder was used as obtained in solution form [124]. This binder can be used at temperatures up to about 1150°C. Figure 7.10 shows the SEM image of alumina microfibers with megasol solution as binder.

7.5.4 Phosphoric acid

Phosphoric acid reacts with alumina fibers to form aluminium metaphosphate [125]. Figure 7.11 shows the SEM image of alumina microfibers with phosphoric acid as binder.
Figure 7.11 SEM image of alumina microfibers with phosphoric acis solution as binder

7.6 Ceramic nanofiber filter medium

The 3.5 g of alumina microfibers and 0.05 g of alumina nanofibers were used to make ceramic nanofiber filter medium with an area ratio of 0.05. The four different binders were tested for this particular ratio. Figure 7.12-7.15 shows the SEM image of ceramic nanofiber filter medium with different binders.

Figure 7.12 SEM image of Ceramic nanofiber filter medium with ceramic microfibers, ceramic nanofibers and B glass fibers as binders.
Figure 7.13 SEM image of Ceramic nanofiber filter medium with alumina rigidizer as binder.

Figure 7.14 SEM image of Ceramic nanofiber filter medium with megasol S50 as binder.
Figure 7.15 SEM image of Ceramic nanofiber filter medium with phosphoric acid as binder.

7.7 Characterization of filter medium

7.7.1 Porosity measurement

Porosity of the filter medium is defined as the ratio of the volume of fibers to the total volume of the filter medium. The porosity value varies from 0 to 1. The porosity value closer to 1 shows that the filter medium are highly porous. The porosity of the filter medium are determined using a special made pycnometer. The porosity is determined from pressure measurements and the ideal gas law. Three pressure readings are taken for empty top chamber, with a 1.0 inch cube and the 6 cm filter medium. The filter medium is placed on the top chamber of the pycnometer as shown in Figure 7.16.
Permeability is a measure of ease of fluid flow through the filter medium. Permeability of filter medium is measured using Frazier air permeability tester (Frazier Precision Instrument Co). Fluid permeability, $K$, is defined by Darcy’s law

$$ Q = K A L \frac{\Delta P}{\mu} \quad (7.1) $$

Where $Q$ is the total volumetric flow rate, $A$ is the surface area through which the fluid passes, $L$ is thickness of medium, $\Delta P$ is the pressure drop across the filter medium and $\mu$ is fluid viscosity. When the flow through the porous medium is not rectilinear
then a geometric shape factor (G) takes the geometry into account, then the Darcy’s law becomes

\[
\text{(7.2)}
\]

Figure 7.17 Frazier air permeability tester

7.7.3 Hardness measurement

Durometer (Type 0, Model 1600, Rex Durometers) measures the hardness of the filter medium. It is the international standard for the hardness measurement of plastic and non-metallic materials. Test procedures for measuring hardness using Durometer are described in American Society for Testing and Material specification ASTM D2240. Table 7.1 and 7.2 gives the average porosity, permeability and hardness values of microfiber filter medium and nanofiber filter medium for an area ratio of 0.5 respectively.
Table 7.1 Characterization of microfiber filter media

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<tbody>
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<td>Alumina Rigidizer</td>
<td>0.9706</td>
<td>1.01E-11</td>
<td>20</td>
</tr>
<tr>
<td>B glass fibers</td>
<td>0.969</td>
<td>3.65E-10</td>
<td>12.33</td>
</tr>
<tr>
<td>Megasol S 50</td>
<td>0.9789</td>
<td>1.29E-11</td>
<td>11.43</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>0.9799</td>
<td>2.32E-10</td>
<td>3.33</td>
</tr>
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</table>

Table 7.2 Characterization of nanofiber filter media for an area ratio of 0.5

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<tbody>
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<tr>
<td>B glass fibers</td>
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<td>11.44</td>
</tr>
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<td>Phosphoric acid</td>
<td>0.9791</td>
<td>2.3E-10</td>
<td>3.41</td>
</tr>
</tbody>
</table>

7.8 Evaluation of different binders using flow rate failure test setup

The main objective is to determine which binder offer better strength to the ceramic filter medium. Therefore, flow rate failure test set up was built to determine the maximum pressure the filter medium can withstand before fibers disintegrate into pieces. Figure 7.18 shows the schematic diagram of the set up. Figure 7.19 shows the actual set up.
Figure 7.18 Schematic diagram of the flow rate failure test setup.

Figure 7.19 Flow failure test setup to test filters made up of different binders.

Figure 7.20 (a) shows the closer view of the setup. The compressed air supplies of varying flow rate are passed through the filter medium by varying pressure regulator (Figure 7.20(b)). The flow rate was increased in steps of 4 psi till the maximum pressure the filter medium can withstand before filter medium disintegrate into pieces and shredded fibers are collected in the wooden box. After each run, the filter holder was disassembled to ensure whether filter medium failed or not. Air velocity is recorded for corresponding pressure for each run. Figure 7.20 (c) shows the disassembled filter holder consist of middle section containing 6 cm filter (Figure 7.20 (e)) and final section with
stainless mesh of 0.25 inch hole size (Figure 7.20 (d)). The assembled filter holder (Figure 7.20 (f)) contains filter in the middle section and mesh with 0.25 inch pore size in the final section.

Figure 7.20 (a) (a) Closer view of flow rate failure test setup. (b) Pressure regulator (c) Disassembled filter holder (d) 6 cm mesh with 0.25 inch hole size (e) Filter holder middle section with 6 cm filter (f) Assembled filter holder with filter in the middle section and steel mesh in the final section.

Figure 7.21 (a) shows another view of the set p with wooden box in the end. The shredded fibers from the experiments are collected in the wooden box using a furnace filter containing nanofibers from espin technologies (Figure 7.21 (b)). The remaining
fibers which are not collected in the filter inside the wooden box are discarded using the pump (Figure 21(c) & (d)).

Figure 7.21 (a) failure flow rate test setup with wooden box to collect shredded fibers (b) A filter inside a wooden box to collect fibers (c) Wooden box exit connected to a pump to remove collected fibers inside the wooden box outside the building.
Figure 7.22 Evaluation of different binders for ceramic microfiber filter medium using setup.

The results shows that ceramic microfiber filter medium did not fail when B glass was used as a binder. The maximum pressure of this setup was 48 psi. Thus, filter medium did not fail up to the pressure of 48 psi when B glass fibers were used as a thermal binder for a mesh with 0.25 inch pore size. Figure 7.23 (a)& (b) shows that filter medium were intact even after exposed to 48 psi.
Figure 7.23 (a) Ceramic filter medium of 6 cm diameter and 2 cm thickness with B glass fibers as binder before flow rate failure experimental runs. (b) Filter medium intact after exposed to 48 psi.

The mesh hole size was varied from 0.25 to 2 inch hole size (Figure 7.24 (a)–(e)) to determine whether holes size provided any mechanical support to the filter medium during the flow rate failure test.
The hole size does seem to have an influence on the filter medium failure pressure. When the B glass fibers were used as a binder for 0.25 inch hole size, the filter
did not break but with the increase in the exposure of flow due to increasing hole size, the filter tends to fail at earlier pressure as show in Figure 7.25.

Figure 7.25 Results from the steel mesh with different hole size for a ceramic microfiber filter medium with B glass fibers as binder.

Similar experiments were carried out for other binders. Only alumina rigidizer as binder was able to hold the fibers together other than B glass when the holes size of mesh was increased from 0.25 inch to 0.5 and 0.75 inch hole size. Filter media made with phosphoric acid and megasol as binder failed when the hole size was increased to 0.5 inch hole size. Alumina rigidizer was the only other binder apart from B glass fibers were able to hold the fibers together when the hole size of mesh was increased from 0.25 to 0.5 and 0.75 inch hole size (Figure 7.26). Ceramic filter medium with alumina rigidizer also failed for higher hole size of the mesh (1.0 and 2.0 inch hole size).
Figure 7.26 Results of the ceramic filter medium with alumina rigidizer as binder for different hole sizes of the mesh.

Binders were also tested for the ceramic nanofiber filter media for the area ratio of 0.5 with different binders for a mesh with a hole size of 0.25 inch (Figure 7.27). The results were almost similar to the ceramic microfiber filter medium for different binders. B glass fibers as binders did not fail during the experimental run and maximum pressure of this setup is 48 psi.
Nanofiber filter media for air filtration applications and ceramic nanofiber filter media for hot gas filtration were successfully fabricated. Different binders were investigated for ceramic filter media and were tested using flow rate failure test setup. B glass fibers as thermal binder works the best and only disadvantage is filter media cannot be used for temperature applications greater than 600°C (melting point of B glass fibers). The next best binder was Alumina rigidizer and it can go up to a temperature of 1600°C.
CHAPTER VIII
Comparison of Experimental and Modeling Results

8.1 Objectives

The objectives of this chapter are

- To compare modeling results of nanofiber filter media with different fiber area ratios with experimental results for air filtration using the Automated Filter Tester (TSI 8130).
- To compare the modeling results of particle loading on microfibrous filter media with experimental results one using the TSI 8130.

8.2 Introduction

Air filters composed of fibrous materials removessolid particulates such as particulate matters, dust, pollen and bacteria, from air. Air filters are used in building ventilation systems, automotive cabin air filters and internal combustion air filters. The performance of nanofiber filter media depends on media physical properties such as fiber diameter, basis weight of nanofibers on a substrate, types of substrate, media uniformity and porosity. Nanofiber filter media developed in our lab are tested for air filtration using the TSI 8130 Automated Filter Tester.
8.3 Basic operating procedure for testing filter media

This section outlines the basic operating procedure for the TSI 8130. Figure 8.1 shows the picture of the TSI 8130. Figure 8.2 displays the internal parts of the TSI 8130. The TSI 8130 can measure efficiencies up to 99.99% using sodium chloride aerosol for air filtration testing. Solid sodium chloride particles are generated from a sodium chloride salt solution and are entrained into air as an aerosol. Filter media are challenged with the solid particles. Dual light scattering photometers measure the upstream and downstream particle concentrations. An internal microprocessor calculates the flow resistance from the measured pressure drop across the filter media for a particular flow rate.
Basic operating procedures are

1. The sodium chloride aerosol is prepared by dissolving 20 g of sodium chloride from Fisher Scientific in one liter of distilled water. This solution is filled into the Aerosol Generator.
Generator and the indicator shows the aerosol level. Care should be taken to make sure sodium chloride aerosol is above the lower level mark (Figure 8.2 (b)).

2. Turn power on

3. The heater option should be selected to generate solid particles.

4. Main regulator pressure is adjusted between 70 to 80 psi on the gauge (Figure 8.2 (c)).

5. Filter holder regulator pressure is adjusted to 20 psi on the gauge (Figure 8.2 (d)).

6. Aerosol generator pressure should read 30 psi when using salt solution (Figure 8.2(e)).

7. Flow meter is adjusted so that make-up air flow rate reads 70 liters per minute for salt solution.

8. Make sure aerosol neutralizer is on.

9. Tester is left on for 30 minutes as a warm up period for salt solution.

10. Tester setup option is selected from menu to perform the test. This test procedure should be repeated until the CF value repeats the same value in the TSI. Usually, the CF value is between 17 to 18. CF value can be viewed under voltage option.

11. Once the constant CF value is obtained, the tester is ready for testing the filter media for solid particles.

8.3 Determination of particle size distribution from the TSI 8130 using a TSI SMPS

8.3.1 Scanning Mobility Particle Size Analyzer (SMPS) unit

Figure 8.3 shows the SMPS unit. The SMPS unit consists of TSI model 3080 Electrostatic classifier (Figure 8.4 a), TSI model 3010 Condensation Particle Counter (CPC) (Figure 8.4 b), Differential Mobility Analyzer (DMA) (Figure 8.4 a) and flow
equalizer (Figure 8.4 c). The SMPS works on the principle of charged particle motion in an electric field. Aerosol flows through a radioactive bipolar charger, creating a bipolar equilibrium charge on the particles. The particles further enter the DMA and are separated according to their electrical mobility. Electrical mobility is inversely related to the particle size. Therefore, small size particles have higher electrical mobility compared to the large particles.

A sample of the aerosol passes through CPC with the help of a suction pump (Figure 8.4d) and the particles are counted in the CPC. The CPC has a butanol (fisher scientific) chamber, in which aerosol is drawn continuously, and butanol is vaporized and diffuses into the aerosol stream. The mixture of aerosol and butanol vapor enters into a cooled condenser where the butanol vapor condenses on the solid sodium chloride particles. Condensation coats the surface of particles and particles are carried by the air flow through an optical detector where they are counted. Care should be taken that number of particles counted by the CPC should not exceed 10,000 and sheath flow rate is usually kept at 2 liters per minutes. The flow equalizer is adjusted so that the sample flow rate is 0.2 liters per minute (Figure 8.4c). An Aerosol Instrument Manager Software is used to acquire the data obtained from CPC. The data are analyzed for measuring the concentration and particle size distribution of the aerosol.
Figure 8.3 SMPS unit
Figure 8.4 Closer view of SMPS unit (a) SMPS unit (b) CPC (c) Flow equalizer (d) Suction pump
8.3.2 Experimental setup to determine particle size distribution

The filter holder was specially designed to test our 6 cm filter media. The filter holder has two ports before and after the filter media to measure inlet concentration as well as outlet concentration of particles by connecting the ports to the SMPS (Figure 8.5(a)). Figure 8.5 (b) shows the filter holder with a 6 cm filter in the center. To determine the particle size distribution, Filter holder (in the TSI 8130) was connected to the SMPS as shown in Figure 8.6 and Figure 8.7. Experimental measurements of particle size distribution, without any filter media, show that most of the particles generated by the 3180 of significant numbers and size are in the range of 25 to 100 nm with a mean of 75 nm. Thus, in our model calculation the particle size of 75 nm is considered (Figure 8.8).

![Figure 8.5(a) Specially designed filter holder to test our 6 cm filter media with inlet and outlet port (b) Filter holder with 6 cm filter media.](image_url)
Figure 8.6 TSI 8130 connected to Scanning Mobility Particle Size Analyzer (SMPS).

Inlet concentration of particles from TSI connected to SMPS

Figure 8.7 Closer view of TSI connected to SMPS.
8.4 Determination of Inlet concentration of particles from TSI 8130

A gravimetric efficiency test was performed as prescribed in the manual to determine the mass concentration of solid particles generated from the TSI 8130. The filter medium of 102 mm diameter was weighed and was found to be 563 mg ($W_1$). The filter medium was placed inside a specially designed gravimetric filter holder. The test was ran at flow rate of 50 liters per minute ($F$) as given in the procedure for 40 minutes ($T$). The filter medium was weighed after the run and was found out to be 593.2 mg ($W_2$).

The Aerosol concentration is determined by using the following formula

$$\text{Aerosol concentration} = \frac{W_2 - W_1}{V} \text{ mg/cubic meter} \tag{8.1}$$

Thus, aerosol concentration of the TSI 8130 is found to be 15.1 mg per cubic meter.
8.5 Comparison of modeling and experimental results for nanofiber filter media for air filtration

The Nanofiber filter media of 6 cm diameter and 1 cm thickness with different ratios of 0.5, 1 and 2 were fabricated as described in Chapter VII. Microfiber filter media of 6 cm diameter and 1 cm thickness were fabricated for comparison with nanofiber filter media. The experiments with different area ratios were repeated three times and Table 8.1 shows the results of nanofiber filter media. The performance of a filter medium is measured by its pressure drop and capture efficiency. The capture efficiency of filter medium is defined as

\[ \text{Quality factor (QF)} \]

Quality factor (QF) is a characteristic measure that takes into account of both capture efficiency and pressure drop of filter medium in one equation and is given by

\[ \text{Relative Quality Factor (RQF)} \]

The Relative Quality Factor (RQF) term is used to compare the nanofiber filter media with microfiber filter media. RQF is calculated by dividing the QF of a filter sample by the QF of a filter with no nanofibers operated at the same conditions.

Table 8.2 gives the average porosity value of nanofiber filter media with different area ratios for 6 cm filter diameter and 1 cm thickness. An area ratio of 0 represents microfiber only filter media. Table 8.1 shows that when a little amount of nanofibers are added to the filter media in the area ratio of 0.5 (0.03 g of nanofibers for 2 g of
microfibers), the capture efficiency of filter media increased from 89 to 96% with least increase in pressure drop of 4 mm of water.

Table 8.1 Performance of Nanofiber filter media with different area ratios

<table>
<thead>
<tr>
<th>Area ratio</th>
<th>Average pressure drop (mm of water)</th>
<th>Average Capture efficiency (%)</th>
<th>Average QF (1/Pa)</th>
<th>Average RQF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>72.73 ± 1.35</td>
<td>89.63 ± 0.73</td>
<td>3.18E-3 + 4.21E-5</td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>76.13 ± 0.90</td>
<td>95.97 ± 0.08</td>
<td>4.30E-3 + 4.13E-5</td>
<td>1.35 ± 0.024</td>
</tr>
<tr>
<td>1</td>
<td>84.94 ± 1.10</td>
<td>97.49 ± 0.05</td>
<td>4.43E-3 + 6.69E-5</td>
<td>1.39 ± 0.038</td>
</tr>
<tr>
<td>2</td>
<td>100.8 ± 1.0</td>
<td>98.46 ± 0.11</td>
<td>4.22E-3 + 3.61E-5</td>
<td>1.32 ± 0.009</td>
</tr>
</tbody>
</table>

Table 8.2 Porosity value of nanofiber filter media with different area ratio

<table>
<thead>
<tr>
<th>Area ratio</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.9789</td>
</tr>
<tr>
<td>0.5</td>
<td>0.9787</td>
</tr>
<tr>
<td>1</td>
<td>0.9783</td>
</tr>
<tr>
<td>2</td>
<td>0.9772</td>
</tr>
</tbody>
</table>

Figure 8.9 shows the quality factor of filter media with different area ratios. The quality factor increases as nanofibers are added to the filter media and reaches a maximum at an area ratio of about 0.5 to 1 and then decreases as further amount of nanofibers added to the filter media. This is because as more nanofibers are added to the
filter media, the increase in the pressure drop exceeds the benefit of improved capture efficiency. Thus, by optimizing the amount of nanofibers added to the filter media, the performance of the filter media is enhanced.

Figure 8.9 shows the RQF versus area ratio of nanofiber filter media.

Figure 8.10 shows the RQF of nanofiber filter media with different area ratios. The RQF is used to compare how the performance of filter medium changes with the addition of nanofibers normalized to a base case.

where, \( \text{QF}_{\text{base}} \) is the Quality Factor of the microfiber filter medium without nanofibers as the basis of comparison. When the RQF >1, nanofiber filter medium perform better than microfiber filter medium.
The RQF plot of experimental and modeling results have similar trend of improved filter performance in the area ratio of 0.5 to 1 (0.03 or 0.06 g in 2g of microfibers). The performance of filter media can be enhanced by optimizing the filter design. Figure 8.11 shows the SEM image of particles collected on microfibers and nanofibers.
Figure 8.11 SEM image of solid particles collected on microfibers and nanofibers.
8.6 Comparison of model and experimental results for particle loading of microfibrous filters media.

Chapter IV discussed about the development of model based on volume averaged continuum theory to predict the filter performance when loaded with solid particles. The particles are collected along the depth of medium and accumulated particles contribute towards the pressure drop and capture efficiency of filter medium. Figure 8.12 shows the SEM image of tiny particles collected on the surface of microfibers. Our model assumes that collected particles act as dendrites (secondary fibers). The SEM image (Figure 8.13) clearly shows the particles are collected as dendrites.

Figure 8.12 SEM image of collected particles on microfibers.
Figure 8.13 Collected particles as dendrites on the surface of microfibers.

The microfibrous filter media of 6 cm diameter and 1 cm thickness with a porosity of 0.96 was fabricated using the vacuum molding process. The loading test was performed using the TSI 8130. The Figure 8.14 and 8.15 shows the capture efficiency and pressure drop trends during the loading time. The capture efficiency of the fibrous filter increases with increase in loading time and experimental and modeling results follows a similar trend. As particles are trapped along the depth of the media, these accumulated particles collect the incoming particles and form dendrites (Figure 8.13) and contribute towards pressure drop across the medium as well as capture efficiency of the medium.
Figure 8.14 Capture efficiency trend during particle loading.

Figure 8.15 Pressure drop trend during particle loading.
8.7 Conclusion

The experimental and modeling results shows that a small amount of nanofibers in the filter media enhances the filter performance. Thus, by optimizing the amount of nanofibers added to the filter media in the area ratio of 0.5 to 1 (0.03 or 0.06 g in 2g of microfibers), the performance of filter media is improved. The experimental and modeling results shows the similar trend for capture efficiency and pressure drop across the media for particle loading. With the increase in loading time, both the pressure drop and capture efficiency increases.
9.1 Conclusions

1. The model was developed based on volume averaged continuum theory to predict the performance of composite filter media consisting of microfibers and nanofibers. The experimental and modeling results indicates that performance of filter media can be improved by adding small amount of nanofibers in the surface area ratio of 0.5 to 1 (0.03 or 0.06 g of nanoofibers to 2g of microfibers) to the filter media. When the small amounts of nanofibers are added, capture efficiency of the filter media improves tremendously with least increase in pressure drop.

2. A model was developed to study the performance of filter media when loaded with solid particles. The modeling and experimental results shows that both capture efficiency and pressure drop increases with increase in particle loading. The accumulated particles along the depth of the media during the particle loading act as secondary fibers that further capture particles and hence contribute towards pressure drop and capture efficiency of the filter media.

3. It is expensive to run experiments at high temperature. Therefore, modeling of fibrous, granular and monolith structures were done to predict which filter structures would perform well for the hot gas filtration in the temperature range of 1000°C. The modeling results predict the fibrous filter to have the least pressure drop among the three filter structures for the same capture efficiency of 99% at room temperature. Due to non
availability of high temperature set up, experiments were done at room temperature and used to validate the model fibrous filters. The model prediction is close to the experimental value for fibrous filter. These shows that makes reasonable prediction for the capture and loading of solid particles. The model was subsequently applied to predict filter performance at high temperatures in the range of 1000°C. Other important results from the model are thickness of the media required for thicker fibers is unrealistic as compared to finer fibers for the same capture efficiency and pressure drop. This result motivated us to develop composite filter media comprising of microfibers and nanofibers.

4. The ceramic nanofiber filter media has a potential application for hot gas filtration. Ceramic nanofibers such as alumina nanofibers were synthesized in our lab which can withstand the temperature in the range of 1000°C.

5. Binders for ceramic filter media should withstand high temperature as well as provide structural support to the media. Flow rate failure test set up was constructed to test filter media with various binders and determine which binder provides more structural support than other binders. Among the various binders tested, ceramic filter media made up of B glass fibers as binders did not fail even at a pressure of 48 psi. The disadvantage of using B glass binder is that media cannot be used for high temperature above 600°C since B melts at about 600°C. The next best binder was Alumina rigidizer which can be used above 1000°C.
9.2 Future work

1. The model developed to predict the filter performance of composite filter media comprising of microfibers and nanofibers did not consider particle loading. The developed model can be extended further to consider particle loading to predict more accurate results.

2. The model developed to predict the filter performance of microfibrous filters during the particle loading do not consider fiber diameter distribution and particle size distribution. Incorporating fiber diameter distribution and particle size distribution will improve the model for better prediction. Particle loading can be extended to predict particle loading for nanofiber filter media for both nanofiber as a thin layer on the surface of the microfiber filter media as well as for the mixed microfiber and nanofiber media.

3. The experiments should be carried out to compare the modeling results of granular and monolith results with experimental one. Modeling results for the fibrous filter were compared with experimental results for one particular condition. A model can be developed for honeycomb monolith structures.

4. Ceramic nanofiber filter media were successfully fabricated and should be tested in hot gas temperature setup for filter performance.

5. While most fibers are negatively charged, alumina nanofibers are positively charged. Therefore, alumina nanofibers can have a potential application as biological filter. Studies should be carried out how the fiber charge affects the filter performance.
6. Comparison of filter performance of nanofibers as a thin layer on the surface of microfiber filter media and same amount of nanofibers as mixed microfiber and nanofiber filter media study should be carried out.

7. Regeneration study on ceramic nanofiber filter media loaded with soot particle should be carried out.
REFERENCES


2. [http://www.epa.gov/air/clearskies/basic.html](http://www.epa.gov/air/clearskies/basic.html) (accessed on May 22, 2010)


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APPENDICES
APPENDIX A

FORTRAN CODE FOR PARTICLE LOADING ON FIBROUS FILTER

! PROGRAM PARTLOAD 1
! THE EFFECT OF LOADING OF PARTICLES ON FILTER PERFORMANCE
! Copyright (c) 2010 Bharath Raghavan and George Chase. All rights reserved
!
!
IMPLICIT REAL (A-H, O-Z)
IMPLICIT INTEGER(I-N)
!
PARAMETER (NPOSN=50, NTIME=360000)
! NPOSN = NUMBER OF POSITION STEPS IN CALCULATION
! NTIME = NUMBER OF TIME STEPS
!
COMMON W(0:NPOSN,0:NTIME),EP(0:NPOSN,0:NTIME),
    ALPHA(0:NPOSN),P(0:NPOSN,0:NTIME),
    ES,DF,DD,DP,VO,DENG,DENP,XLAMDA,VIS,DIFF,DT,DZ,
    RD,RF,RSLIP,RMOLEC,RKN,PI,PO,RKND,WO,FZ(NPOSN)
!
! MAIN PROGRAM
    CALL INIT
    CALL CALC
    CALL CALP
    CALL RESULTS
END
  !
  ! INITIALIZE VARIABLES
  SUBROUTINE INIT
  IMPLICIT REAL (A-H, O-Z)
  IMPLICIT INTEGER(I-N)
  
  ! PARAMETER (NPOSN=50, NTIME=360000)
  COMMON W(0:NPOSN,0:NTIME),EP(0:NPOSN,0:NTIME),
  ! ALPHA(0:NPOSN),P(0:NPOSN,0:NTIME)
  COMMON ES,DF,DD,DP,VO,DENG,DENP,XLAMDA,VIS,DIFF,DT,DZ,
  ! RD,RF,RSLIP,RMOLEC,RKN,PI,PO,RKND,WO,FZ(NPOSN)
  ! CONSTANTS
  PI = 3.142857
  ! WRITE(*,*) PI
  WO = 0.0000126 ! INLET MASS FRACTION PARTICLES IN GAS
  ES = 0.02 ! VOLUME FRACTION OF FIBERS IN FILTER
  DF = 5.E-6 ! FIBER DIAMETER, M
  DD = 150.E-9 ! PARTICLE DENDTRITE DIAMETER, M
  DP = 75.E-9 ! PARTICLE DIAMTER, M
  VO = 0.0457 ! FACE VELOCITY, Q/A, M/S
  T = 294. ! TEMPERATURE, K
  BOLTZ = 1.381E-23 ! BOLZMANN CONSTANT, J/MOLECULE/K
  PO = 1. ! REFERENCE PRESSURE (INLET PRESSURE), ATM
  GMW = 29.0 ! GAS MOLECULAR WEIGHT (AIR), KG/KGMOL
  RGAS = 0.08205 ! GAS LAW CONSTANT, ATM M3/KGMOL/K
  DENP = 2165.! KG/M3
  DT = 1.0E-3 ! TIME STEP SIZE, SECONDS
  XL = 1E-2 ! FILTER THICKNESS, M
  
  ! CALCULATE POSITION STEP SIZE
  X = NPOSN
  DZ = XL/X
  ! CALCULATE MEAN FREE PATH AND GAS DENSITY
  DENG = PO*GMW/RGAS/T ! GAS DENSITY, KG/M3
  ! WRITE(*,*) DENG
  XLAMDA = 2.31548E-10*T/PO !M
  ! GAS VISCOSITY USING LEONARD JONES (BSL2 APP E AND EQ 1.4-14)
  EK = 97 !K
  TSTAR = T/EK !-
  ! WRITE(*,*) TSTAR
  OMEGA = 1.16145/TSTAR**0.14874
  OMEGA = OMEGA + 0.52487/EXP(0.7732*TSTAR)
  OMEGA = OMEGA + 2.16178/EXP(2.43787*TSTAR)
  ! WRITE(*,*) OMEGA
  SIGMA = 3.617 !ANGSTROMS

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\[
\text{VIS} = 0.000026693 \times (\text{GMW} \times T)^{0.5} / \text{SIGMA} / \text{SIGMA} / \text{OMEGA} \quad \text{G/CM/S}
\]
\[
\text{VIS} = \text{VIS}/10. \quad \text{KG/M/S}
\]

\![\text{WRITE(*,*) VIS}]

\! \text{CALCULATE DIFFUSIVITY OF PARTICLES (BSL2 EQ 17.4-3)}

\[
\text{DIFF} = \text{BOLTZ} \times T / 6. / 3.1415927 / (\text{DP}/2.) / \text{VIS} \quad \text{M}^2/\text{S}
\]

\! \text{SET VALUES IN ARRAYS}

\! \text{DO I=0, NPOSN}

\! \text{DO J=0, NTIME}

\! \text{W(I,J)=0.0! PART MASS FRACTION IN GAS}

\! \text{EP(I,J)=0.0! PART ON FIBERS VOLFRACTION}

\! \text{P(I,J) = PO}

\! \text{ENDDO}

\! \text{ENDDO}

\! \text{DO J=0,NTIME}

\! \text{W(0,J)=WO ! SET INLET MASS FRACTION}

\! \text{WRITE(*,** W(0,J)}

\! \text{P(0,J)=PO ! SET INLET PRESSURE}

\! \text{ENDDO}

\! \text{RETURN}

\! \text{END}

\!

\! \text{CALCULATE FILTER COEFFICIENT ALPHA}

\! \text{SUBROUTINE CALPHA(J)}

\! \text{IMPLICIT REAL (A-H, O-Z)}

\! \text{IMPLICIT INTEGER(I-N)}

\! \text{PARAMETER (NPOSN=50, NTIME=360000)}

\! \text{COMMON W(0:NPOSN,0:NTIME),EP(0:NPOSN,0:NTIME),}

\! \text{ALPHA(0:NPOSN),P(0:NPOSN,0:NTIME),}

\! \text{COMMON ES,DF,DD,DP,VO,DENG,DENP,XLAMDA,VIS,DIFF,DT,DZ,}

\! \text{RD,RF,RSLIP,RMOLEC,RKN,PI,PO,RKND,WO,FZ(NPOSN) }

\! \text{DO I=1,NPOSN}

\! \text{EG=1.-ES-EP(I,J)}

\! \text{WRITE(*,** I,J,EG}

\!changing i = o to 1 (april 15)

\! FIBERS

\! THIS CORRELATION WORKS FOR CONTINUUM AND SLIP

\! FLOW

\! WHEN KN IS SMALL THE SLIP EFFECTS ARE NEGLIGIBLE

\! NO CORRELATION AVAILABLE FOR MOLEC FLOW \quad \text{BROWN PP 107-108}
AFIB = 4.*ES/3.1415927/DF ! ALPHA FIBER
RKN = 2.*XLAMDA/DF ! KNUDSEN NUMBER
ZETAP = -0.5*LOG(1-EG)-0.52+0.64*(1-EG)+1.43*EG*RKN
! HARD TO DETERMINE IF EG OR ES SHOULD BE
! USED TO CALCULATE ZETAP. HERE WE USE EG.
PE = DF*VO/EG/DIFF
DR = DP/DF
ER = 1.0/(1.+DR)-(1+DR)+2.*(1+DR)*LOG(1+DR)
ER = ER+2.86*RKN*(2.+DR)*DR/(1+DR)
ER = ER*(1/2./ZETAP)
ED = 2.7/PE**(0.667)*(1.+0.39/
(ZETAP*PE)**0.333*RKN)
EDRP = 1.24*DR**(0.667)/(ZETAP*PE)**0.5
EFIB = ED+ER+EDRP

! DENDRITES
ADEND = 4.*EP(I,J)/3.1415927/DD ! ALPHA FIBER
! WRITE(*,*) ADEND
RKN = 2*XLAMDA/DD ! KNUDSEN NUMBER
ZETAP = -0.5*LOG(1-EG)-0.52+0.64*(1-EG)+1.43*EG*RKN
PE = DD*VO/EG/DIFF
DR = DP/DD
ER = 1.0/(1.+DR)-(1+DR)+2.*(1+DR)*LOG(1+DR)
ER = ER+2.86*RKN*(2.+DR)*DR/(1+DR)
ER = ER*(1/2./ZETAP)
ED = 2.7/PE**(0.667)*(1+0.39/(ZETAP*PE)**0.333*RKN)
EDRP = 1.24*DR**(0.667)/(ZETAP*PE)**0.5
EDEND = ED+ER+EDRP

ALPHA(I) = AFIB*EFIB+ADEND*EDEND
! WRITE(*,*) I,J,ALPHA(I)
ENDDO
RETURN
END
! CALCULATE CONCENTRATION PROFILES
SUBROUTINE CALC
IMPLICIT REAL(A-H, O-Z)
IMPLICIT INTEGER(I-N)
!
PARAMETER (NPOSN=50, NTIME=360000)
COMMON W(0:NPOSN,0:NTIME),EP(0:NPOSN,0:NTIME),
ALPHA(0:NPOSN),P(0:NPOSN,0:NTIME)
COMMON ES,DF,DD,DP,VO,DENG,DENP,XLAMDA,VIS,DIFF,DT,DZ,
RF,RD,RSLIP,RMOLEC,RKN,P1,PO,RKND,WO,FZ(NPOSN)
!
DO J=0,NTIME-1 ! INCREMENT OVER TIME
!
! CALCULATE ALPHA USING THE PREVIOUS TIME STEP CONC
CALL CALPHA(J)
!
! CALCULATE GAS CONCENTRATIONS
! write(*,*)' i j eg c alpha w(i,j)'
DO I=1,NPOSN-1 ! INCREMENT OVER POSITION
! changing i = 0 to 1 (april 15)
! APPLY MACCORMACK METHOD TO DISCRETIZE THE
! PDE (Elizabeth Stephan Dissertation 1999 pg 28)
EG=1.-ES-EP(I,J)
!WRITE(*,*) EG
C=DT*VO/EG/DZ
IF(C.GT.1.0)THEN
WRITE(*,*)' WARNING - CURRANT COND VIOLATION'
PAUSE
ENDIF
W1=W(I,J)-C/2.0*(W(I+1,J)-W(I-1,J))
W2=C*C/2.0*(W(I+1,J)-2.0*W(I,J)+W(I-1,J))
W3=ALPHA(I)*DZ*C/2.0*(W(I+1,J)+W(I-1,J))
W(I,J+1)=W1+W2-W3
! WRITE(*,*) I,J, W(I,J+1)
IF(W(I,J+1).LT.0.0) THEN
W(I,J+1) = 0.0000000001
WRITE(*,*) I,J, W(I,J+1)
ELSE
W(I,J+1)=W1+W2-W3
ENDIF
W(0,J) = WO
!
! write(*,*)i,j,eg,c,alpha(i),w(i,j)
ENDDO
!
! AT EXIT
I=NPOSN
W1=W(I,J)-C*(W(I,J)-W(I-1,J))
W3=ALPHA(I)*DZ*C*W(I,J)
W(I,J+1)=W1-W3
IF(W(I,J+1).LT.0.0) THEN
W(I,J+1) = 0.0000000001

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ELSE
W(I,J+1) = W1-W3
ENDIF
W(0,J) = WO
!
! CALCULATE DENDRITE VOLUME FRACTION
DO I=1,NPOSN ! INCREMENT OVER POSITION
!
EP(I,J+1) = EP(I,J) + DT*ALPHA(I)*DENG/DENP*VO*W(I,J)
!WRITE(*,*) I,J,W(I,J)
ENDDO
W(0,J) = WO
ENDDO
RETURN
END

SUBROUTINE CALP
IMPLICIT REAL(A-H, O-Z)
IMPLICIT INTEGER(I-N)
!
PARAMETER (NPOSN=50, NTIME=360000)
COMMON W(0:NPOSN,0:NTIME),EP(0:NPOSN,0:NTIME),
a ALPHA(0:NPOSN),P(0:NPOSN,0:NTIME),
COMMON ES,DF,DD,DP,VO,DENG,DENP,XLAMDA,VIS,DIFF,DT,DZ,
a RF,RD,RSLIP,RMOLEC,RKN,PI,PO,RKND,WO,FZ(NPOSN)
!
! RESISTANCE DUE TO FIBERS
DO J = 0,NTIME-1
!
! CALCULATE DENDRITE VOLUME FRACTION
CALL CALPHA(J)
DO I = 1,NPOSN
!CALL CALPHA(J)
P(0,J) = PO
!
EG = 1.- ES-EP(I,J)
!WRITE(*,*) I,J,EP(I,J)
!PAUSE
!
RKN = 2*XLAMDA/DF
IF(RKN.LT.0.01) THEN
RF = (4.*PI*VIS)/((-0.5*LOG(ES))-0.738+ES)
! WRITE(*,*) RF
ELSEIF(RKN.LT.0.25) THEN
RF = (4.*VIS*PI*(1.+ (1.996*RKN)))/(-0.5*LOG(ES)-0.75+ES
a -((ES*ES)/4.)+ 1.996*RKN*(-0.5*LOG(ES)-0.25+(ES*ES/4.)))
! WRITE(*,*) RF
ELSEIF((RKN.GT.0.25).AND.(RKN.LT.10)) THEN
RMOLEC = (2.29*PI*VIS)/10
RSLIP = (4.*VIS*PI*(1+1.996*0.25))/(-0.5*LOG(ES)-
a 0.75+ ES - (ES*ES/4)+
a 1.996*0.25*(-0.5*LOG(ES)-0.25 + (ES*ES/4.)))
RF = (((RMOLEC-RSLIP)*(RKN-0.25))/(10-0.25))+RSLIP
!WRITE(*,*) RF
ELSE
RF = (2.29*PI*VIS)/RKN
! WRITE(*,*) RF
ENDIF

! RESISTANCE DUE TO DENDRITES
RKND = 2.*XLAMDA/DD

IF(RKND.LT.0.01) THEN
RD = (4.*PI*VIS)/((-0.5*LOG(EP(I,J)))-0.738+EP(I,J))
ELSEIF(RKND.LT.0.25) THEN
RD = (4.*VIS*PI*(1+1.996*RKND))/(-0.5*LOG(EP(I,J))-0.75+EP(I,J)*EP(I,J)/4.)
+ 1.996*RKND*(-0.5*LOG(EP(I,J))-0.25 + (EP(I,J)*EP(I,J)/4.)))
ELSEIF((RKND.GT.0.25).AND.(RKND.LT.10)) THEN
RMOLEC = (2.29*PI*VIS)/10
RSLIP = (4.*VIS*PI*(1+1.996*0.25))/(-0.5*LOG(EP(I,J))-0.75+EP(I,J)*EP(I,J)/4.)
+ 1.996*RKND*(-0.5*LOG(EP(I,J))-0.25 + (EP(I,J)*EP(I,J)/4.)))
RD = (((RMOLEC-RSLIP)*(RKND-0.25))/(10-0.25))+RSLIP
! WRITE(*,*) EP(I,J)

ELSE
   RD = (2.29*PI*VIS)/RKND
ENDIF

! DRAG FORCE DUE TO FIBERS AND DENDRITES (DRAG FORCE PER EG
FZ(I)= (-4.*VO*DZ/(PI*EG))*((ES*RF/(DF*DF))+ (EP(I,J)*RD/(DD*DD)))

FZ(I) = FZ(I)*9.86231693E-6

! LOCAL PRESSURE
   P(I+1,J) = P(I,J) + FZ(I)
   P(I,0) = PO

ENDDO

DO I =1,NPOSN
   EP(I,J+1)=EP(I,J)+DT*ALPHA(I)*DENG/DENP*VO*W(I,J)
ENDDO

P(0,J) = PO
   W(0,J) = WO
ENDDO

RETURN
END

! WRITE RESULTS !
SUBROUTINE RESULTS
IMPLICIT REAL (A-H, O-Z)
IMPLICIT INTEGER(I-N)

! PARAMETER (NPOSN=50, NTIME=360000)
COMMON W(0:NPOSN,0:NTIME),EP(0:NPOSN,0:NTIME),
a ALPHA(0:NPOSN),P(0:NPOSN,0:NTIME)
COMMON ES,DF,DD,DP,VO,DENG,DENP,XLAMDA,VIS,DIFF,DT,DZ,
a RF,RS,RSLIP,RMOLEC,RKN,PI,PO,RKND,WO,FZ(NPOSN)
OPEN(UNIT=7, FILE='C:\TEMP\CONC.DAT', STATUS='UNKNOWN')
J = NTIME-1
    WRITE(7,900)J
    WRITE(7,901)
    DO I=0,NPOSN
    WRITE(7,902)I,W(I,J),EP(I,J),P(I,J)
    ENDDO
RETURN
900 FORMAT(1X,'TIME STEP = ',I8)
901 FORMAT(1X,'POSN STEP',1X,'GASMF',1X,'VOL PART F',1X,'LOCAL PRESS')
902 FORMAT(1X,I8,4X,E10.4,4X,E10.4,4X,E10.4)
END
APPENDIX B
CHARACTERIZATION OF FILTER MEDIA WITH DIFFERENT BINDERS

Microfiber filter media

<table>
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<tr>
<th>Binder</th>
<th>Porosity</th>
<th>Permeability</th>
<th>Hardness</th>
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<td>0.969</td>
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<tr>
<td>Megasol S 50</td>
<td>0.9789</td>
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Nnaofiber filter media with an area ratio of 0.5

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<th>Hardness</th>
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APPENDIX C
TEST RESULTS FOR FILTER MEDIA WITH DIFFERENT BINDERS USING FLOW RATE FAILURE TEST SETUP

Results for 0.25 inch hole size for b glass fibers as binders

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<th>Air velocity (m/s)</th>
<th>Failure</th>
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